

# Environmental Impact of Space Launches and Societal Response

by  
Elwyn Sirieys

Submitted to the Department of Aeronautics and Astronautics  
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Author .....  
Department of Aeronautics and Astronautics  
and the Institute for Data, Systems, and Society  
May 6, 2022

Certified by .....  
Olivier de Weck  
Apollo Program Professor of Astronautics and Engineering Systems  
Thesis Supervisor

Accepted by .....  
Jonathan P. How  
R. C. Maclaurin Professor of Aeronautics and Astronautics  
Chair, Graduate Program Committee

Accepted by .....  
Noelle E. Selin  
Professor, Institute for Data, Systems, and Society  
and Department of Earth, Atmospheric and Planetary Sciences  
Director, Technology and Policy Program



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## Abstract

Space-based technologies can be valuable assets for environmental protection and for supporting Sustainable Development Goals (SDGs) on Earth. However, these activities have their own share of environmental impacts. Throughout their life cycle, launch vehicles affect their local and global environments both on Earth and in space. In particular, they generate direct emissions of combustion products into every layer of the atmosphere, inducing ozone depletion and radiative forcing. Recent literature indicates that these consequences of space launches are understudied, especially considering the space industry's projected growth. This thesis aims at assessing the situation in terms of current and future environmental impact, as well as society's response to the issue.

A historical analysis of space launch vehicle designs is conducted, based on a comprehensive record of 6,502 orbital launches for the period 1957-2021, to inform on technological evolution and implications in terms of emissions. This study suggests that, as part of today's unprecedented diversity in rocket designs, key decisions regarding engines and propellants are being made which will decide the future atmospheric impact of the industry. Trends in the space sector are analyzed and scenarios are generated to assess the future situation.

For the first time, societal response to this issue is analyzed quantitatively and compared with three case studies in the automotive industry, the satellite industry, and aviation. A total of 463,630,586 news articles, 771,604 legal documents, 10,836,398 academic publications over 30 years were examined.

Alternative paths forward are proposed to foster a more sustainable future for the space launch industry, in terms of actionable design choices, impact assessment methodologies, regulatory options, and market-based incentivization mechanisms based on a sustainability index for launch vehicles.

Thesis Supervisor: Olivier de Weck

Title: Apollo Program Professor of Astronautics and Engineering Systems

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As I look back on the past three years, I am pleased to say that I got more than I imagined possible from my time at MIT – in parts because I gave more than what would be considered reasonable, too. I will keep these acknowledgments to a minimum, as what truly deserves to be told in person doesn't need to be put on paper.

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Our research on the environmental impact of space launches, partly presented in this thesis, wouldn't have been possible without the help of many. Thank you to Airbus, and especially to Thierry and Matthieu, for supporting my work for the past two years – and, for almost a hundred times, listening to me talking about rocket propulsion and design optimization. Thank you to Martin Ross from Aerospace Corporation for his precious advice and a couple of invigorating conversations about the future of rocket emissions. Thank you to Chloe Gentgen, Julia Milton, and Asha Jain from ESL, who joined to write for the MIT Science Policy Review: parts of this thesis directly rely on the research we conducted during that time.

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# Chapter 1

## Introduction

### 1.1 Preamble

How do human activities in space affect Earth's environment? How can we mitigate this impact? The following thesis stemmed from the scarcity of thorough, quantitative answers to these simple but fundamental questions.

As any human activity develops, it generates externalities with local and sometimes global consequences. Some of these will result in negative environmental impacts. In recent human history – in particular during the industrial age – these impacts have rarely been anticipated, even less addressed, with the timeliness and effort that their future incidence on the well-being of society could justify. Examples can be found across all industries: from the decline in air quality observed in cities due to internal combustion engines used for transportation, to the growing risks from space debris generated in Earth's orbits.

There is a multiplier effect to acting in the early stages of these issues, as not only the time-integrated burden is reduced, but technological advancements are made towards a sustainable direction, avoiding any type of penalizing technological inertia. In 2020, we started a rigorous search for such a sector in the space industry where highly consequential technological and strategical choices were being made today, with a potential for widespread impact on society in the next decade to come, and comparatively low levels of environmental awareness. The satellite industry did fall

into this category four decades ago, at the time when the issue of space debris generation just started being discussed [8], with little to no mitigation strategy implemented for a long time. Today, the fast-growing and fast-changing space launch industry, on the question of atmospheric emissions, falls into this category as well. The choice of such an approach to adopt a research subject is also an attempt at developing the most valuable skills and expertise to effectively tackle the human challenges of the next decades. By construction, such a research effort would necessitate adding to the aerospace engineering discipline, environmental science, and (science-based) policymaking, among others. MIT, with its leading role in environmental matters in the aerospace industry, in research related to climate change and more generally on societal challenges involving both technical expertise and policymaking, is in an ideal position to conduct this work.

This thesis constitutes an attempt at assessing the situation of space launch activities in terms of current and future environmental impacts, and society’s response to it.

## 1.2 Motivation

The year 2021 was a turning point for the private spaceflight industry – often referred to as NewSpace. Among the commercial firsts in the space sector, two companies (Blue Origin and Virgin Galactic) began to offer space tourists tickets for suborbital spaceflights. SpaceX achieved a record number of launches – including the first all-civilian spaceflight – and NASA awarded contracts for new private space station concepts. Projects of mega-constellations are also in development, to provide global internet services. The proposed number of satellites in these constellations continues to grow with SpaceX considering up to 30,000 satellites in their Starlink constellation [9]. For reference, only 1300 active satellites were orbiting Earth in 2015. But as the commercial space industry flourishes, offering new services to people and businesses on Earth, it also generates its share of negative environmental externalities.

Space-based technologies can be valuable assets for environmental protection and

for supporting Sustainable Development Goals (SDGs) on Earth. However, these technologies have their own share of environmental impacts. Recently, advancements in space policy have been focused on the in-space pollution that satellites and rocket bodies produce in the orbital environment. While orbital debris (or space junk) may well be viewed as the most consequential threat from space activities today [10], the appropriate scope to understand the full environmental cost of the expanding space industry also encompasses ground and atmospheric consequences. Researchers have called for further study on rocket emissions [11, 12] – the combustion gases and particles emitted into different layers of the atmosphere during launches and reentries of rockets – which interact with ozone chemistry and affect global climate in poorly understood ways [12]. While the scientific understanding is limited, studies suggest that the impact of rocket emissions will continue to grow with increased launches [11, 13].

This growth will be supported by an explosion of the number of launch vehicle manufacturers, offering both smaller, more responsive options (Rocket Lab’s Electron, ASTRA’s Rocket 3, Vector Launch’s Vector-R, etc.) and larger ones (Starship, SLS, New Glenn, etc.) for larger-scale missions. This diversity of new launch vehicles will be critical in enabling the development of LEO constellations for telecommunications and remote sensing, space tourism, the deployment of new space stations, and human missions to the Moon and Mars, in addition to defense applications. The increase in the number of manufacturers also led to the emergence of new rocket engines and new propellant choices which deserve attention from an environmental standpoint.

Legal responses to any perceived environmental impacts of space launches have been almost nonexistent for decades. But as the industry gains visibility, and the commercial segment expands, policymakers have started to raise questions. Over the summer of 2021, following ambivalent reactions from the public regarding space tourism activities, novel space tax policies were proposed in the US to collect federal [14] and local [15] taxes for space tourism, citing environmental concerns.

This context, summarized in Fig. 1-1, urges the need for an assessment of the current and future environmental impact of space launches, as well as of society’s

response.




Industry	Current EIA Capability*	Existence of mitigation strategies*	CAGR est. 2019-2025**
	■ ■ ■ ■ ■	■ ■ ■ ■ □	2-5%
	■ ■ ■ □	■ ■ □ □	3-5%
	■ □ □ □	■ □ □ □	<b>13-20%</b>

Figure 1-1: Comparative evaluation of the current capability in the automotive industry, aviation, and the space launch industry to conduct effective environmental impact assessments (EIA), and have mitigation strategies in place already. Sources: Morgan Stanley, Mc Kinsey, Airbus.

\*: Grading based on aggregated metrics from publicly available documents.

\*\* : Compound Annual Growth Rate (CAGR) of each industry. Pre-covid estimates.

## 1.3 Approach

### 1.3.1 Research questions

In order to assess the situation regarding the current and future environmental impact of space launches, as well as society’s response to it, we focus on the following research axes:

- What is the environmental impact of space launches on Earth?
- How is society responding to this issue?

### 1.3.2 Thesis overview

This section provides a brief overview of the organization of this thesis and each chapter’s contribution to the two research questions.

- **Chapter 1** introduces the rationales and global context demonstrating the importance of researching the environmental impact of space launches. Guiding questions are presented, as well as the structure of the thesis and its main contributions to the domain
- **Chapter 2** offers a review of the multiple ways launch vehicles can have an impact on their local and global environment, with a thorough focus on emissions from launch events and their known global atmospheric impact. A historical analysis of space launch vehicles since 1957 is conducted to inform on the technological developments and their meaning in terms of emissions. Current trends in the space sector are analyzed and scenarios are generated to inform an assessment of the expected situation regarding the launch vehicles' future impact
- **Chapter 3** proposes an evaluation of the societal response to the environmental challenges presented by the space launch industry. A comparative analysis is conducted with the automotive industry, aviation, and the satellite industry. Three indicators are used to characterize this response quantitatively: the levels of research activity, public awareness, and policymaking activity during the period 1990-2021. A complete overview of the current policy environment on the matter of rocket emissions is given. The paper provides an analysis of these trends throughout time and across industries, and more importantly suggests interrelationships and sensitivities to diverse factors. Lessons are drawn for the future of the space launch industry
- **Chapter 4** draws from the past analyses to offer alternative ways forward ensuring a more sustainable future for the space launch industry. First, in terms of rocket engineering, actionable design alternatives are offered to develop the next generation of launch vehicles. The importance of improving and implementing impact assessment methodologies, supported by new research on the topic, is emphasized. The idea of a sustainability index for launch vehicles is proposed. The regulatory potential of this topic is studied, and policy alternatives are

investigated, including market-based options

- **Chapter 5** concludes with the assessment conducted of the current and future environmental impact of the space launch industry, and the characterization of the societal response. Research areas for future work are presented and prioritized

### 1.3.3 Main contributions

- Historical analysis of launch vehicles' design evolution from 1957-2022 and their implications regarding future atmospheric emissions
- Comparative study of the societal response to negative environmental externalities from four different industries, including the space launch industry for the period 1990-2021, using quantitative methods
- Comprehensive overview of the local and global policy landscape addressing environmental impacts from space launches. Analysis of regulatory challenges and future policy alternatives
- Introduction of the idea of a sustainability index for space launch vehicles based on life cycle assessment methods

# Chapter 2

## The environmental impact of launch vehicles

The growth of the space launch industry leads to increased impacts at every step of the life cycle, affecting local environments on the ground as well as the global environment – above and below the Kármán line. This chapter offers an overview of the multiple ways launch vehicles can have negative environmental externalities, with a thorough focus on emissions from launch events and their known atmospheric impact. The goal is to assess and inform on the current nature and magnitude of the issue, with the current state of the art, and give perspectives for the further future.

### 2.1 Rocket science and emissions

The impacts resulting from space launch activities originate from the production of propellants, from components manufacturing, assembly, integration, and testing, but also from the launch, and the vehicle disposal [16]. By emitting particles directly in the stratosphere and higher, the launch event has an impact that is distinctive among any other human activities and therefore requires particular attention, for it is scarcely understood and could become significant. The environmental impact of rocket launches, specifically the atmospheric emissions of combustion products, is the focus of this work (see Tab. 2.1).

Table 2.1: Overview of sub-research areas and prioritization of atmospheric emissions from launches for the present work, over four selection criteria

Research Area	Knowledge Gaps	Lack of mitigation strategies	Relative importance to other sources of pollution (in the environment affected)	Shared characteristics among launchers	References
Local env. effects	+	+	+++	++	[17, 18, 19, 20, 21]
Global env. effects (launch excluded)	++	++	+	+	[22]
Effects of launch emissions	+++	+++	++++	++	[23, 24, 25]

Several factors determine the nature, volume and impact of a rocket’s atmospheric emissions. These include most importantly the type and mass of propellant, the engine design, but also the trajectory and launchpad location. Since launch vehicles can be used for diverse purposes, ranging from short suborbital flights, to delivery of small satellites, to crewed spacecraft around Earth and beyond, these factors vary immensely. To give a couple of examples, Rocket Lab’s Electron – one of the smallest orbital rockets on the market – measures 18 m tall with about 11.3 t of propellant, and successfully flew 5 times in 2021 to deliver about 300 kg of small satellites payload to LEO [26, 27, 28]. On the other hand, the Space Launch System (SLS), NASA’s super heavy-lift expendable launch vehicle, stands at 111 m with a combined propellant mass of over 2,500 t and can inject up to 45 t of payload – including crewed capsule Orion – to lunar vicinity in its most powerful configuration [29, 30]. When comparing the atmospheric impact of launchers, there is a necessity to account for the mass of payload sent to orbit along with the targeted orbital regime, to perform a meaningful analysis.

The trajectory of a launch vehicle through the atmosphere is linked to the orbit in which the payload is delivered. Depending on their target orbit, launch vehicles emit through nearly all layers of the atmosphere – troposphere (up to 10-15 km), stratosphere (10-15 to 45-55 km), mesosphere (45-55 to 80-90 km), thermosphere (80-90 to 500 km) and exosphere (above 500 km) [31]. These layers correspond to large variations in temperature and pressure, and their thickness and boundaries vary

depending on the coordinates and the time of the year. As a reference, civil aviation operates near the tropopause, which delineates the troposphere and the stratosphere. Due to the differences in temperature and pressure between the atmospheric layers, gas exchange is extremely slow. Therefore, the altitudes of emissions are important because not only do they correspond to the altitudes where there is potential for major interactions with atmospheric chemistry, but also there is a risk for accumulation [31].

Emissions in the stratosphere are a particular source of concern, because it contains 90 % of the atmospheric ozone ( $O_3$ ), with the highest concentrations found in the ozone layer (from 15-35 km) [32]. Stratospheric ozone acts as a natural protection for Earth, absorbing most of the ultraviolet radiation coming from the Sun, which is harmful to life [33]. Human-generated compounds have well-documented direct effects on the ozone layer; in the mid-1970s, measurements linked the use of chlorofluorocarbons (CFCs) to large ozone holes in Antarctica. In reaction, the Montreal Protocol was created in 1987 to regulate the use of these substances [32]. Since then, the ozone layer is closely monitored and its importance in protecting life on Earth is agreed upon in the scientific community.

Rocket propellants and engines are major design choices and play the largest role in governing a rocket's atmospheric impact. Table 2.2 summarizes the most common propellants and examples of launchers using them. The two most common types of rocket propellants are liquid bipropellants and solids. Liquid bipropellants consist of a liquid fuel and a liquid oxidizer that are mixed and react together in the combustion chamber. Solid rocket motors (SRMs) consist of a solid mixture in the form of grains stored within the combustion chamber that burns once ignited. For both types of propulsion, a chemical reaction generates hot gases and particles that are accelerated and ejected to produce thrust [34]. Recent years have seen an important development of liquid oxygen (LOx)/Methane engines, especially among future reusable launch vehicles. Figure 2-3 shows the breakdown of total annual number of successful orbital launches since 1957 by propellants.

The combustion products emitted in the atmosphere also depend on the characteristics of the engines. The mixture ratio of an engine – also called oxidizer to fuel

(O/F) ratio – is defined as the mass flow of oxidizer divided by the mass flow of fuel. Most engines do not operate at a stoichiometric mixture ratio (optimum amount for a reaction with no deficiency or excess of reagents), but instead, run fuel-rich. This results in a higher-efficiency engine (higher specific impulse). The optimum mixture ratio is specific to each engine and will influence the proportions of products in the exhaust flow [34]. During the combustion, the high heat will additionally decompose the product molecules into simpler constituents, capable of recombining themselves, before attaining an equilibrium state. Lastly, once ejected from the engine, the exhaust plume will mix in the ambient air, which can lead to afterburning (or secondary combustion) of the remaining fuel [35] and new reactions with the molecules present in the atmosphere. Rocket emissions hence vary with engine designs and depend on complex plume chemistry, which is still an active research area today. In the next section, Table 2.3 presents the main combustion products of each propellant and their potential impact when emitted in the different layers of the atmosphere.

Due to their staged configuration, rockets can rely on several engines and propellants. Rocket staging is used to increase the efficiency of the rocket and typically, rockets have between two and four stages. After being ignited on the launchpad, the first stage will consume all its propellant during ascent (in the case of an expandable rocket) and will then be jettisoned, before the next stage is ignited. The last stage contains the payload and fairings. In addition, boosters can be attached to the first stage as an additional source of thrust. The boosters and lower stages will come back to Earth’s surface, fall into the sea, or land propulsively if they are reusable. Upper stages and fairings, which often have achieved high-enough speed to stay in orbit around the Earth for some time, often end up reentering the atmosphere where they will partially decompose (Figure 2-2). The boosters and different stages are largely independent and can rely on different types of propellants. SRM propulsion is used for boosters and some last stages, while liquid propulsion is common for first and second stages. The payload launched to orbit and the target orbit drives the design of a rocket’s staging configuration, including propellant mass for each stage.

Mission performance, cost, and reliability have been the key figures of merit (FoM)

driving rocket design since the beginning of the space age. Sustainability is at best a secondary consideration in the launch vehicle market today. However, design choices – especially engine architecture and propellant mix – can induce radically different impacts on the environment, as shown in the next section.

## 2.2 Literature Review

In 2022, scientific understanding of the environmental impact of atmospheric emissions from space launches is very scarce. This observation is reported in most publications, including very recent ones [12, 11] which highlight the need for more research efforts in this direction. It is especially true regarding the nature and magnitude of the global contribution of these emissions to ozone depletion and climate change [36].

This situation is essentially the consequence of a historical assumption that because so few launches occur every year, this impact could be disregarded [11]. The strategic nature of space activities in the context of the second half of the XX<sup>th</sup> century also ensured a low political willingness to investigate. Finally, progress in understanding higher-atmosphere chemistry and climate modeling are recently removing some of the technical blockers to a better understanding of rocket emissions.

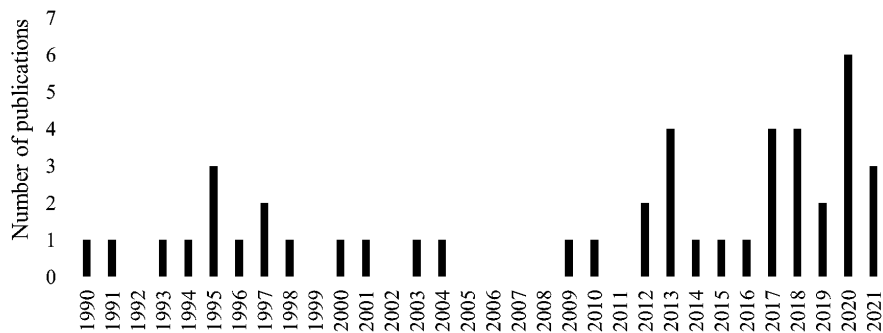


Figure 2-1: Annual number of peer-reviewed scientific publications addressing specifically the global atmospheric impact of space launches, since 1990

Figure 2-1 shows the number of peer-reviewed research papers published since 1990 and addressing the atmospheric impacts of space launches. The total number of papers is below 40 and two main periods of activity can be identified: the first one

in the mid-1990s – the busiest years of the Space Shuttle era –, and the other one starting in the early 2010s and accelerating in the very last few years. Table 2.4 lists nearly all publicly available scientific, engineering, or legal papers directly addressing aspects of the impact of atmospheric emissions from space launches.

Tables 2.2 offers a summary of the rocket propellants in use today and the main corresponding launch vehicles (past, current or future). Table 2.3 offer a summary of all global atmospheric impacts identified in the literature associated with the propellant choices detailed above.

Figure 2-2 offers an overview of the launch and reentry phases of a rocket’s life cycle through layers of the atmosphere, and the main effects identified in the literature.

Table 2.2: Common rocket propellants and examples of rockets using them, either launched since 2020 or in development (\*). (X) indicates which stage(s) of the rocket use(s) that propellant, with (0) being the boosters. Only the boosters and the first two stages were included. Table from: [1]

<b>Propellants</b>	<b>Type</b>	<b>Rocket example</b>
Liquid Oxygen ( $LOx$ ) Liquid Hydrogen ( $LH_2$ )	Liquid	Ariane 5 ECA (1,2), Atlas V (2), Delta IV Heavy (0,1,2), New Glenn* (2), SLS* (1,2), Vulcan* (2)
Liquid Oxygen ( $LOx$ ) Kerosene ( $RP-1$ )	Liquid	Atlas V (1), Electron (1,2), Flacon 9/Heavy (0,1,2) Long March 6/7(0,1,2), Soyuz 2 (0,1,2)
Nitrogen Tetroxide ( $N_2O_4$ ) UDMH $\pm$ Hydrazine ( $N_2H_4$ )	Liquid	Long March 2/3/4 (0,1,2), Proton (1,2)
Liquid Oxygen ( $LOx$ ) Methane ( $CH_4$ )	Liquid	New Glenn* (1), Starship* (1,2), Vulcan* (1)
Ammonium Perchlorate ( $NH_4ClO_4$ ) Alumnium ( $Al$ ) $\pm$ PBAN or HTPB	Solid	Ariane 5 ECA (0), Atlas V (0), SLS* (0)

Table 2.3: Common rocket propellants, main combustion products, and identified atmospheric impacts. Concentration of combustion products emitted and resulting magnitude of the impacts varies significantly by launch vehicle. Several exhaust products have the same type of environmental impacts, but not severity. From: [1]

<b>Propellants</b>	<b>Main Products</b>	<b>Important and Studied Environment Impacts</b>
Liquid Oxygen ( <i>LOx</i> ) Liquid Hydrogen ( <i>LH<sub>2</sub></i> )	<i>H<sub>2</sub>O, H<sub>2</sub>, OH,</i> <i>NO</i>	Cloud Formation
Liquid Oxygen ( <i>LOx</i> ) Kerosene ( <i>RP-1</i> )	<i>CO<sub>2</sub>, H<sub>2</sub>O, CO<sub>x</sub>,</i> <i>OH, NO<sub>x</sub>, soot</i>	Ozone Changes Radiative forcing Cloud Formation
Nitrogen Tetroxide ( <i>N<sub>2</sub>O<sub>4</sub></i> ) UDMH ± Hydrazine ( <i>N<sub>2</sub>H<sub>4</sub></i> )	<i>H<sub>2</sub>O, N<sub>2</sub>, CO<sub>2</sub>,</i> <i>NO<sub>x</sub>, soot</i>	Ozone Changes Radiative forcing Cloud Formation
Liquid Oxygen ( <i>LOx</i> ) Methane ( <i>CH<sub>4</sub></i> )	<i>H<sub>2</sub>O, CO<sub>2</sub>, CO,</i> <i>NO</i>	Radiative forcing Cloud Formation
Ammonium Perchlorate ( <i>NH<sub>4</sub>ClO<sub>4</sub></i> ) Aluminum ( <i>Al</i> ) ± PBAN or HTPB	<i>HCl, H<sub>2</sub>O, CO<sub>x</sub>,</i> <i>NO<sub>x</sub>, Al<sub>2</sub>O<sub>3</sub>, soot</i>	Ozone Changes Radiative forcing Cloud Formation

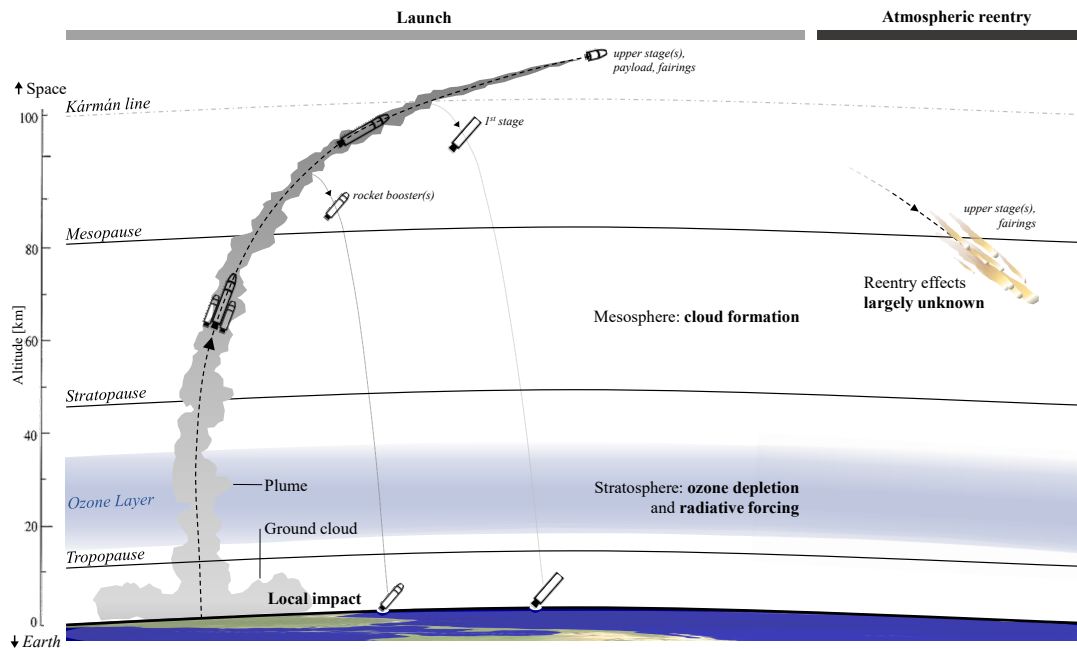


Figure 2-2: Trajectory of a typical space launch vehicle through atmospheric layers during the ascent trajectory and atmospheric reentry, with indications of the known local and global environmental impacts. Objects are not to scale. The altitude of the various atmospheric layers is indicative and varies with the latitude. First stage and boosters are generally discarded after their return to the surface, unless the rocket is (partially) reusable. Environmental impacts shown above are not the results of a single type of launch vehicles but rather results of studies investigating a variety of launch vehicles. Figure from: [1]

Table 2.4: Research publications addressing the global impact of atmospheric emissions from space launch vehicles in three disciplines: Science, Engineering, Law (1982-2021)

Title	Year	First author
Experimental techniques for characterization of particles in plumes of sub-scale solid rocket motors	2021	Carlotti, S
From life cycle assessment of space systems to environmental communication and reporting	2021	Wilson, A
Quantification of transformation products of rocket fuel unsymmetrical dimethylhydrazine in air using solid-phase microextraction	2021	Bukenov, B
Satellite mega-constellations create risks in Low Earth Orbit, the atmosphere and on Earth	2021	Boley, A
Application of environmental life cycle assessment (LCA) within the space sector: A state of the art	2020	Maury, T
Comparative Analysis of Climate Forcing and Ozone Depletion Caused by Emissions from Two Different Suborbital Launch Systems	2020	Ross, M
Experiments for collection and characterization of particles exiting from solid propellant rocket nozzles	2020	Maggi, F
Spaceborne Limb Observations of Artificial Aerosol Clouds	2020	Gorkavyyi, N
The environmental impact of emissions from space launches: A comprehensive review	2020	Dallas, J
The Sustainable Commercialisation of Space: The Case for a Voluntary Code of Conduct for the Space Industry	2020	Chrysaki, M
The Coming Surge of Rocket Emissions	2019	Ross, M
Environmental life cycle assessment of commercial space transportation activities in the united states	2018	Neumann, S
Rocket emissions representation in atmospheric air-quality models: The short-range atmospheric transport and reaction of gases released by solid propellant engines	2018	Schuch, D
The environmental impact of space transport	2018	Korolvea, T
The policy and science of rocket emissions	2018	Ross, M
Global atmospheric response to emissions from a proposed reusable space launch system	2017	Larson, E
The use of an atmospheric model to simulate the rocket exhaust effluents transport and dispersion for the centro de lançamento de alcântara	2017	Schuch, D
Radiative forcing caused by rocket engine emissions	2014	Ross, M
Bracing for the impending rocket revolution: how to regulate international environmental harm caused by commercial space flight	2013	Friedberg, J
Multidisciplinary approach for assessing the atmospheric impact of launchers	2013	Koch, A
Characterization of HTPB-based solid fuel formulations: Performance, mechanical properties, and pollution	2013	DeLuca, L
Earth observation from space – The issue of environmental sustainability	2013	Durrieu, S
Impact of rocket exhaust plumes on atmospheric composition and climate — an overview	2013	Voigt, C
On the uncertainties in assessing the atmospheric effects of launchers	2013	Murray, N
Bright polar mesospheric clouds formed by main engine exhaust from the space shuttle’s final launch	2012	Stevens, M
Space Commercialization: The Need to Immediately Renegotiate Treaties Implicating International Environmental Law	2012	Davis, A
Potential climate impact of black carbon emitted by rockets	2010	Ross, M
Limits on the space launch market related to stratospheric ozone depletion	2009	Ross, M
Environmental impact assessment and space activities	2004	Viikari, L
Ozone depletion caused by NO and H <sub>2</sub> O emissions from hydrazine-fueled rockets	2004	Ross, M
Global stratospheric effects of the alumina emissions by solid-fueled rocket motors	2001	Danilin, M
Observation of stratospheric ozone depletion associated with Delta II rocket emissions	2000	Ross, M
A global modeling study of solid rocket aluminum oxide emission effects on stratospheric ozone	1998	Jackman, C
Effects of launch vehicle emissions in the stratosphere	1997	Brady, B
Observation of stratospheric ozone depletion in rocket exhaust plumes	1997	Ross, M
Space shuttle ’s impact on the stratosphere : An update	1996	Jackman, H
Atmospheric Impact of Liquid Oxygen and Kerosene Engines	1995	McCaleb, R
On the atmospheric impact of launching the Ariane 5 rocket	1995	Jones, A
The need for international agreements concerning the ozone depleting effects of chemical rocket propulsion	1995	Shapiro, L
Better protection of the ozone layer	1994	Ko, M
Atmospheric effects of chemical rocket propulsion	1991	AIAA
The Impact of International Outer Space Commerce on the Environment	1991	Manson, H
The Space Shuttle’s impact on the stratosphere	1990	Prather, M
Ionospheric effects of rocket exhaust products—heao-c, skylab	1982	Zinn, J

## 2.3 Industry trends

Current consensus on the level of rocket emissions is that its atmospheric impact is still very limited relative to other industries, but likely not negligible anymore. If the space industry grows as it is expected to, this impact will soar over the next decade and a lot of time will have been lost to mitigate the impact. Considering that it is today that design choices determining the future fleet of launch vehicles are being made, this invites to an assessment of the future impact of the space launch industry.

### 2.3.1 Technological evolution

In this section, we conduct a historical analysis of technological evolution in rocket science, focusing on propulsive technologies (the main driver of atmospheric emissions). We interpret this evolution from the angle of atmospheric emissions and use this analysis to inform our forecasts of the direction taken by the industry, and the subsequent assessment of the future situation.

The fundamentals of rocketry date back to more than a millennium ago, in what is today's China and Greece, mainly for warfare purposes. The technology re-emerged in the XVII<sup>th</sup> and XVIII<sup>th</sup>, during which their theoretical bases were expanded. It's then at the end of the XIX<sup>th</sup> century that the spectrum of applications of rocket science was expanded, concepts for space exploration were formulated, and advanced chemistry experiments and prototypes were tested. After significant progress over the first half of the XX<sup>th</sup> century accelerated by the Second World War, the Soviet Union reached orbit in 1957, launching the first satellite – Sputnik 1. They were closely followed by the United States in 1958, launching Explorer 1 on a modified Jupiter-C military prototype [37].

The following analysis relies on a comprehensive database of all successful orbital launches conducted during the period 1957 to 2021. Launch data was gathered from two main publicly available sources [2, 3], and complementary research was done to identify and classify all corresponding launch vehicle families, sub-families, and variants. A focus on engine technologies – and especially propellant choices – was

taken to regroup launch vehicles by comparable designs.

Figure 2-5 shows an overview of this analysis. The large volumes of launches during the period 1960-1990 were due to the space race and a significant portion of these were military launches using ICBM (Inter-Continental Ballistic Missile) designs. The long development time of launch vehicles (about a decade on average) is visible on the plot, where one can follow the emergence of new prototypes and the end of others, often used for decades and derived into different versions with propulsion changes, payload mass capacity changes.

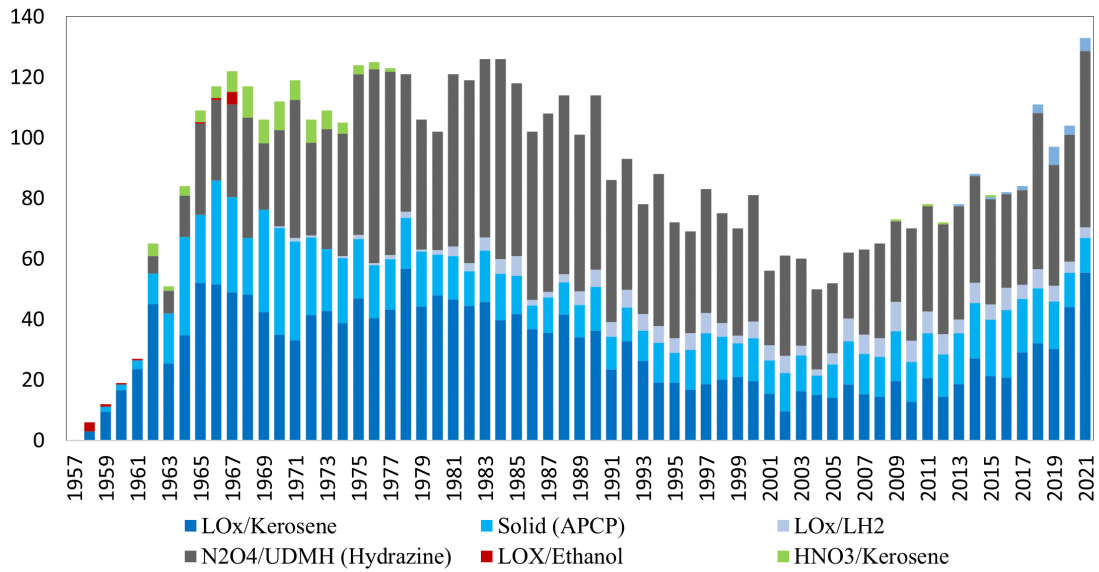


Figure 2-3: Total number of successful orbital launches worldwide per year (1957-2021), broken down per main type of propellants used for first stages and boosters. The number of launches during the period 1960-1990 is largely inflated by defense missions, while the 54% growth since 2001 is essentially driven by commercial missions. Table from: [1]. Data from: [2, 3].

Although rocket engines were continuously improved and optimized for thrust, Isp, reliability and cost, the rate of technological developments on rocket engines experienced two golden ages, in the 1960s and today. The first one was marked by the first orbital flight ever (using LOX/Kerosene), the first successful flight of LOx/LH2 engines to orbit in 1962 on Centaur, and the first successful flight of Saturn V (using the largest engines ever designed) in 1967. As visible on Figure 2-3, many types of propellants and combinations were experimented during the 1960s period. Thousands

of mixtures of Ethanol and LOX, Kerosene and HNO<sub>3</sub>, sometimes combined with hydrazine were tested (see classification on Figures 2-3 and 2-4).

At the end of the 1970s, only four main types of propellants remained used (excluding NEPE-75), and the others were abandoned. Today, the pace of technological evolution on rocket engines is again skyrocketing. The diversity in launch vehicle designs has never been higher. For the first time since several decades, a new type of propulsion will probably reach orbit (Methane/LOx) and will likely take a significant role in tomorrow's fleet of launch vehicles. This inflection point in technological evolution is a critical moment for key design directions to be taken. And regarding rocket engine technology, these will be highly consequential in deciding the future significance of the environmental impact of space launches.

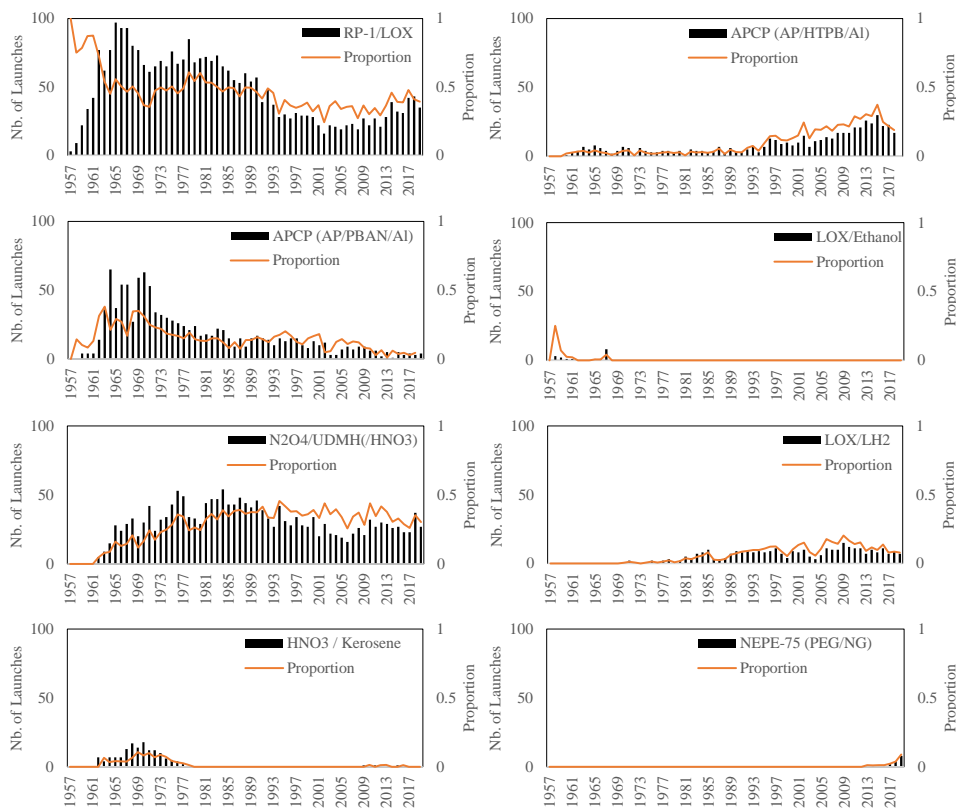


Figure 2-4: Shifts in rocket propellants used for orbital launch vehicles (1957-2021), for first stages and strap-on boosters). Bar chart of the number of uses per type of propellant every year, and plot of their proportion among all launches that year.

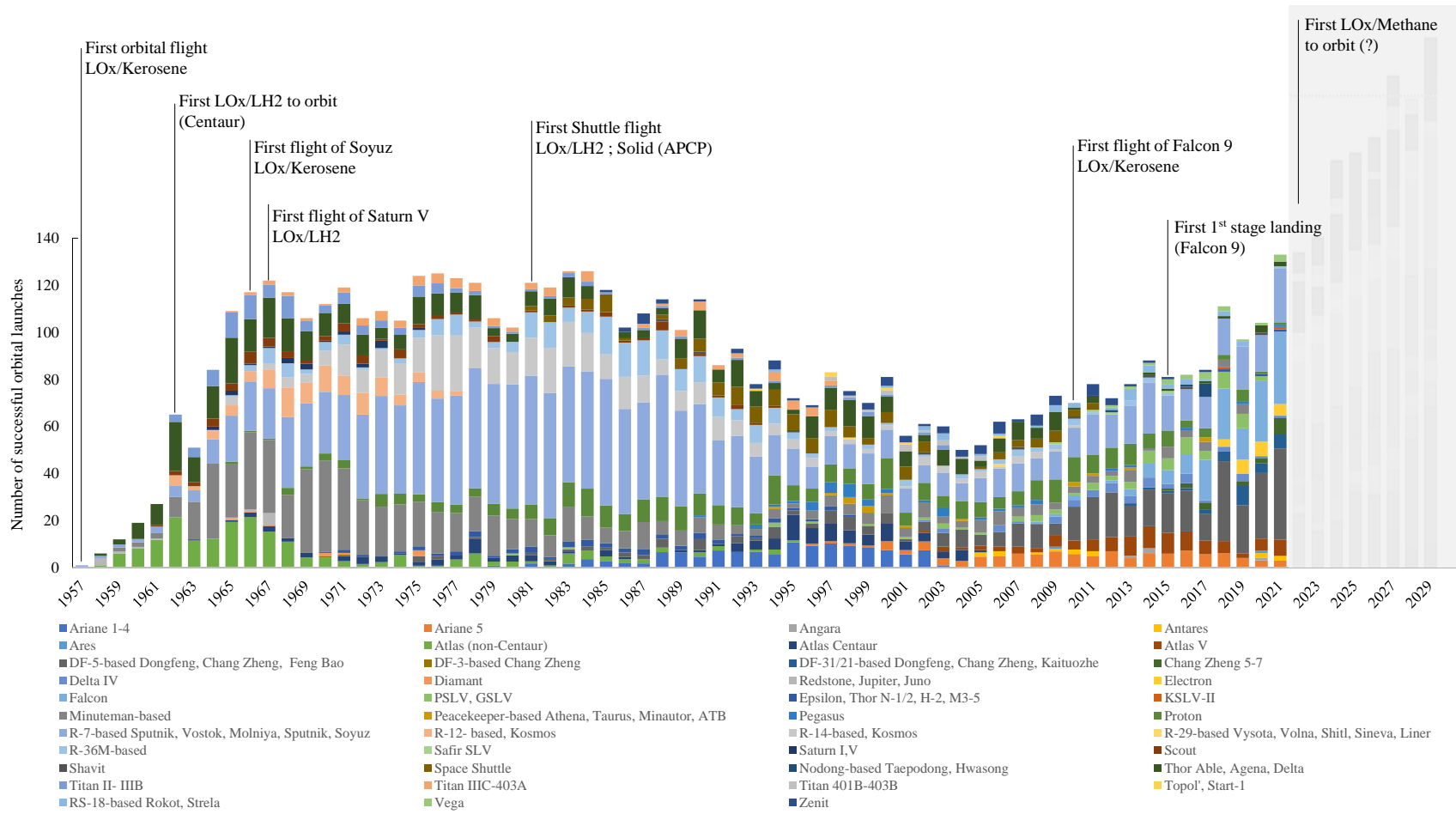


Figure 2-5: Comprehensive overview of all successful orbital launches for the period 1957-2021 worldwide. Breakdown per launcher family and reorganized to account for significant design changes affecting the engine and propellants. Timeline of some of the main milestones in rocket propulsion history. Data from: [2, 3].

### 2.3.2 The future fleet of launch vehicles

The emergence of a New Space economy has created numerous applications for commercial ventures in space, all of which rely on launchers to get into orbit. This competitive landscape has spurred innovation and breakthroughs such as new designs of reusable launch vehicles, development of smaller, low-cost satellites and small launchers, leveraging new manufacturing techniques and materials. Figure 2-6 shows the number of payloads deployed per year peaking over the past five years (the main contribution to this peak coming from the deployment of SpaceX’s Starlink constellation).

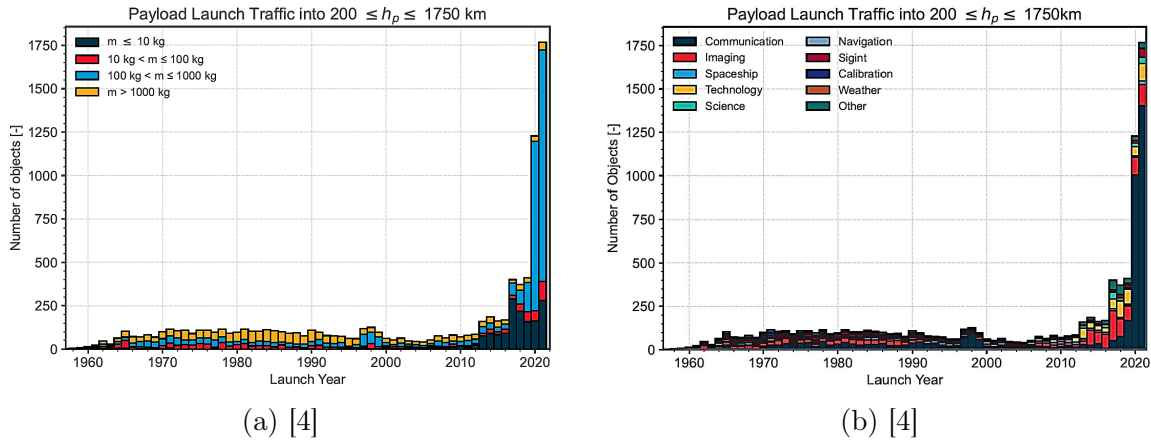


Figure 2-6: Number of payloads launched to LEO (1957-2021) – breakdown by mass and function performed. Courtesy of ESA [4].

Launch costs have decreased significantly in the last few decades – SpaceX’s Falcon 9 rocket currently sends payload to low Earth orbit (LEO) for \$2,700 /kg [38], compared with estimated costs of \$36,600 /kg to launch payload to LEO on a Delta II rocket (active from 1989-2018) in 2018 [39]. As a direct consequence of that, recent years have seen a strong increase in the number of commercial launches, reaching an all-time high in 2021 (Figure 2-5).

In this context, what will the global fleet of launch vehicles look like in 2030 or 2040 is likely being designed today, or has been envisioned in the past few years. Based on market forecasts for the global space industry from UBS, Morgan Stanley, and Goldman Sachs, processed by IDA [5], we build a baseline growth scenario for the

space launch industry. Many alternative scenarios are conceivable, but we focus on the one of highest likelihood, situated between (a) and (b) [5], where the analysis of the future environmental impact is also the most critical (see Figure 2-7).

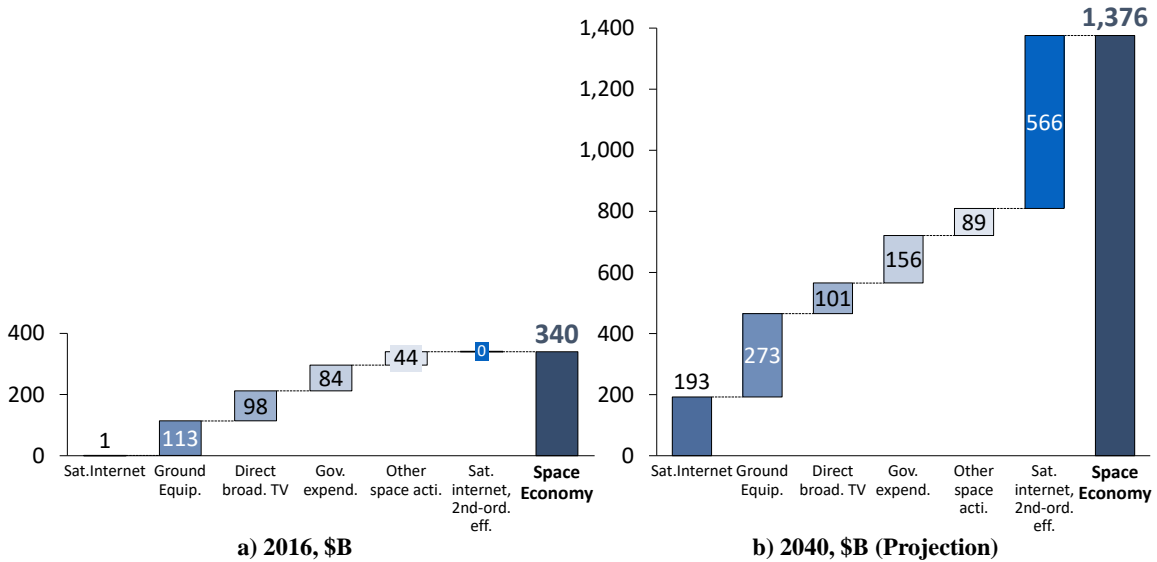


Figure 2-7: Size of the global space economy: estimate for 2016 and projections for 2040 by UBS and Morgan Stanley, by space economy [5]. Breakdown by market segment, already existing or enabled by New Space capacities.

We refine this analysis by focusing on propellant choices for future launch vehicles, as it is the main driver of their atmospheric emissions. Forecasting is made using current fleet characteristics, as well as recent developments and announcements from launch vehicle manufacturers, including rocket sizes, development timeline, launch frequencies, reusability, and propellant types.

Considering the competitiveness of the launch services market, all developments will not make it to market, and all growth announcements will be a function of the rest of the market. For this reason, we deliberately model an attenuated ramp-up and scaled it to global estimated size that year based on the CAGR previously fixed (see Scenario 0 – used as a "as-is" comparison case and scenario 1 in Figures 2-9 and 2-10).

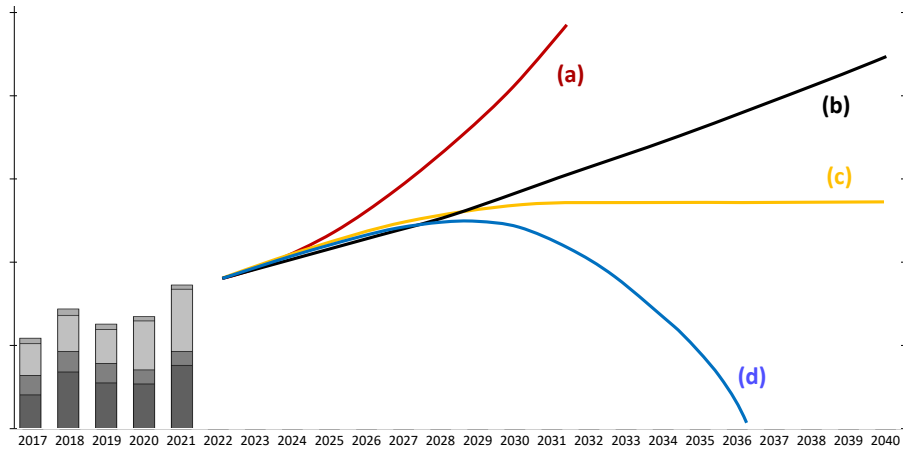


Figure 2-8: Future scenarios for the evolution of the number of space launches every year post-2021 and until 2040 (schematic). Scenario (a) corresponds to an acceleration of the launches, (b) corresponds to a continued growth scenario, (c) to a progressively stabilizing number of launches, and (d) a collapse of the launch industry [6].

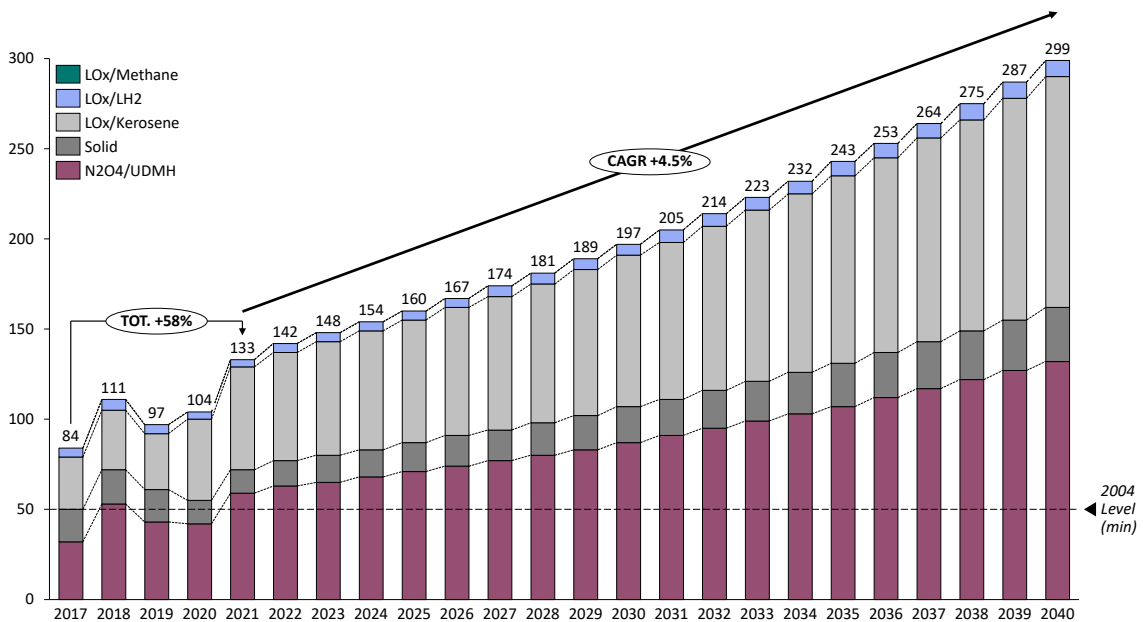


Figure 2-9: Number of launches per year, projection for 2022-2040 based on space economy growth forecast, actual data for 2017-2021. *Scenario 0* (hypothetical): breakdown of the types of propellants used stays identical to 2021 levels.

The future space launch industry is very likely to see a fast-growing LOx/Methane reusable rocket segment appear in the coming years, which will ultimately cover a significant portion of all launches, especially in the United States in the near future (Starship, Vulcan Centaur, Neutron and New Glenn)2-11. The impact from this type

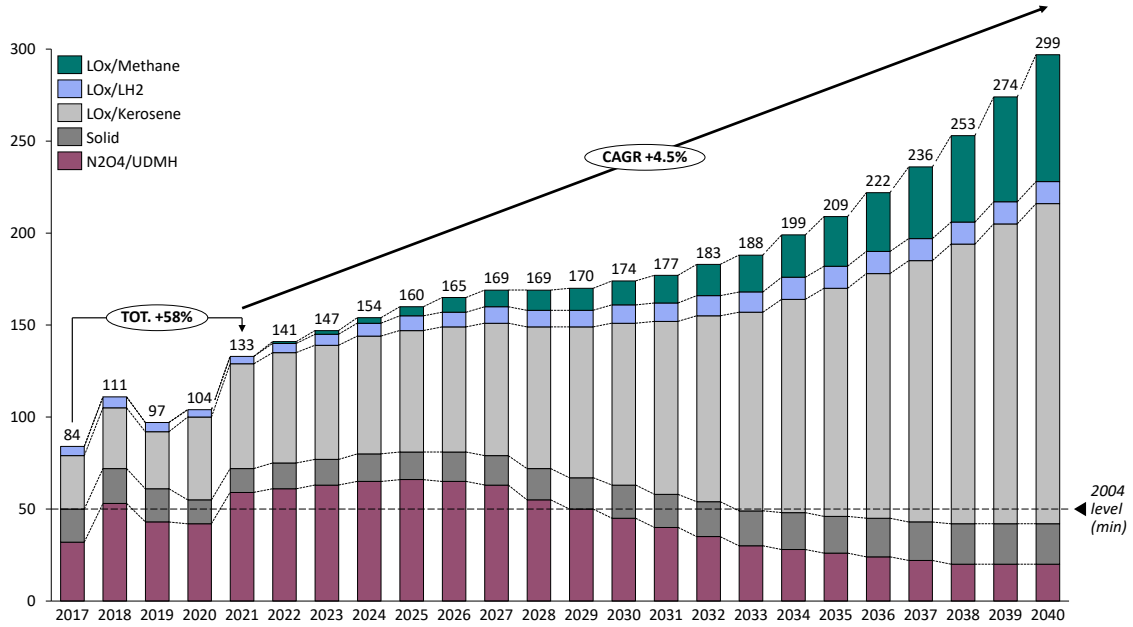


Figure 2-10: Number of launches per year, projection for 2022-2040 based on space economy growth forecast, actual data for 2017-2021. *Scenario 1* : breakdown of the types of propellants evolves as the global fleet of launch vehicles shifts rapidly to propellant choices enabling effecting reuse of rocket stages; development of LOx/Methane-based launchers at moderate speed; progressive entry in service of already announced heavy and super-heavy launchers, along with a small fleet of small launchers using LOx/Kerosene and LOx/Methane essentially

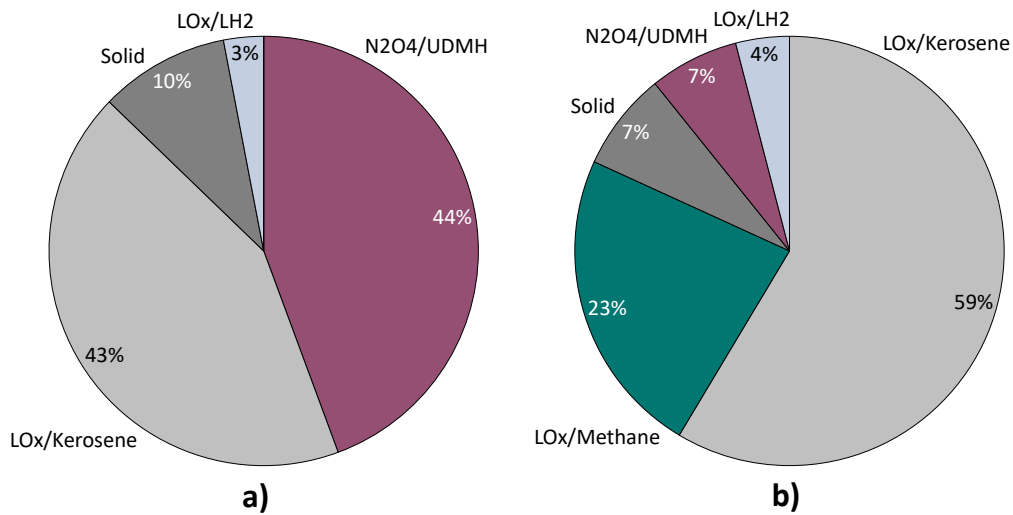


Figure 2-11: Decomposition of the future 2040 fleet of launch vehicles by propulsion type. *Scenario 0* represented on Fig. a) and *scenario 1* on Fig. b).

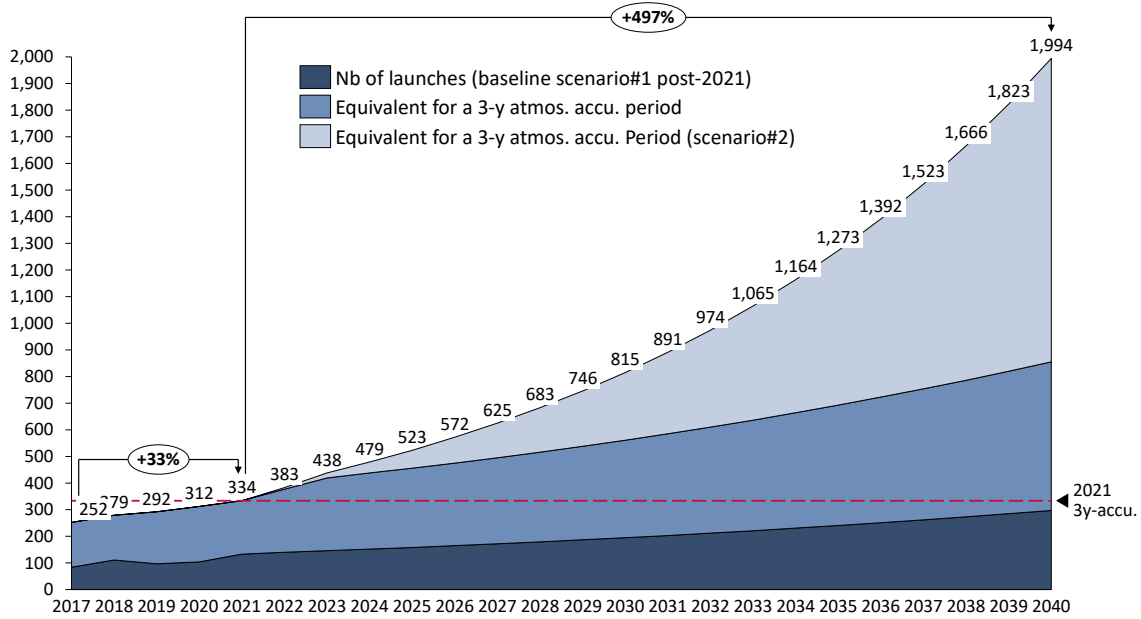


Figure 2-12: Effect of atmospheric accumulation over 3 years to the resulting yearly volume of emissions for *scenario 0 and 1* and for "*scenario #2*" (based on the larger Goldman Sachs estimate [5]). Types of propellants not accounted for.

of propulsion needs to be further investigated, but theoretically should be less harmful than LOx/Kerosene for its near-absence of black carbon emissions. It also appears that the launch services market is likely to naturally get rid of hypergolic propellants, very harmful for the environment. The number of rockets relying on LOx/LH2 – very clean emissions – is expected to grow with SLS and Ariane 6 becoming soon operational, but these shouldn't take a significant volume of the market ultimately. This mode of propulsion is however often associated, when used as a first stage, with solid rocket boosters, which are linked with ozone depletion and radiative forcing. LOx/Kerosene, very popular for new manufacturers and convenient for reusable stages' propulsion, should become increasingly popular. These will be problematic for their emissions of black carbon which can have strong radiative forcing effects.

Because of the characteristics of atmospheric layers mentioned earlier, these emissions will however accumulate and make the impact generated by this growth of the launch industry even larger (see Figure 2-12).

# Chapter 3

## Societal response

Society, when faced with the negative environmental externalities of some of its activities, can respond in different and intricate ways. These responses are characterized by their effectiveness to solve the issue in question, both in time and resources, and can involve very diverse branches of society. Regulation, investments in research and development, media coverage, among others, are all instances of this phenomenon. This is no different on the topic of the environmental impacts of the space launch industry. Studying this response, in the light of other comparable issues addressed today and in the past, informs us of the forces at play, their adequacy in form and magnitude, their likelihood to effectively address the problem, and the areas of improvement.

### 3.1 Background

As a society, we tend to act late and with limited success on the global environmental issues generated by our activities, even when their future incidence on the well-being of society could justify the effort [40, 41, 42, 43, 44, 45]. Since the beginning of the industrial era, the actions taken to mitigate the effects of human activities have overall been rather ineffective relative to the magnitude of their impacts: on climate, biodiversity, and air quality, among others [40, 46].

As new technologies were developed, and as new industries were created, a similar pattern went repeating. New products, vehicles, and infrastructures were rarely

designed to minimize their environmental footprint. This is well translated through the use of the term "environmental externalities" in Economics, which communicates that they are not part of the picture and therefore, that they were not taken into consideration by any of the manufacturers. In many cases, this was perfectly acceptable early on from the perspective of societal well-being. Indeed, the volumes were often very small, the level of environmental awareness very low, and the technical challenges too constraining. In a nascent automotive industry, designing a Ford Model T for only cost and performance was legitimate. This applies similarly to the early days of aviation, or the early days of the satellite industry, with an absence of concern about respectively their impact on climate or the multiplication of space debris.

The awareness and subsequent call for action on these aspects came later. They emerged as the technologies developed and the sectors grew, because of local or global health issues, accidents, scientific studies, or simply because of the rise in the general level of public awareness on environmental issues. Early warnings were often inconsequential, and no incentive was created to push toward the most beneficial direction for society's well-being. These are often cases of tragedies of the commons [47], as independent action from individual actors according to their self-interest negatively affected a shared resource, against the common good. Progressively, branches of society became aware of these issues and allocated resources in this direction: academic research, media coverage, policymaking, environmental activism, etc. As a whole, society directed efforts to understand and tackle these environmental issues.

This type of effort is far more effective when they happen early in the development cycle of an industry because environmental considerations are then intrinsic to technological advancements. In such context, electric vehicles or hydrogen-powered aircraft may have seen faster technological progress. Technological inertia towards fossil fuel-dependent solutions would be reduced, too. As a result, the environmental impact of cars and aviation would likely be more manageable than it currently is. The importance of early design choices, in the development of any new system and thus of the industry revolving around it, cannot be ignored as part of today's effort to minimize negative environmental externalities on Earth.

The notion of societal response is very useful to analyze from a systems perspective the way situations are addressed in an organized community at a macroscopic level. It has been used in the past in very diverse research areas, in sociology and environmental science especially, for instance, to characterize the reaction to new religious movements, [48] or natural and technological hazards [49]. Both qualitative and quantitative analyses can be conducted, and metrics be developed to assess and compare meaningful aspects of the response in different contexts, by different societies, to different issues.

Assessing the nature and magnitude of the societal response to the environmental impact of the space launch industry is therefore highly valuable as a way to evaluate the ability of society to anticipate future problematic situations, and its capacity to act on them. Through this notion, we also can draw informative and precise lessons from the way negative environmental externalities from other industries were handled.

## 3.2 Methodology

A comparative study of the societal response to negative environmental externalities from four different industries (automotive industry, aviation, satellite industry, and space launch industry) is conducted for the period 1990-2021. These sectors have been selected for suitability to be compared, at different levels, to the space launch industry. They also experimented (or are still experimenting) a fast period of growth, and are associated with growing environmental impacts (see 3.1). The 1990-2021 period has been chosen because it encompasses very informative periods for the four industries in question, and for data availability reasons.

Three metrics are chosen here to characterize societal response quantitatively: the levels of research activity, public awareness, and policymaking activity. The level of research activity is measured for each year through the proportion of research papers being published to address the topic in question, among the total number of research papers published. It is therefore a metric of the resources being assigned and the relative research effort being dedicated to this particular topic. Similarly, policymak-

Table 3.1: Industrial sectors and negative environmental externalities within the scope of the comparative analysis conducted

<b>Industry</b>	<b>Negative Environmental Externalities within the Scope of the Study</b>
Automotive Industry	Air Pollution, Climate Change
Aviation	Climate Change
Satellite Industry	Orbital Debris
<i>Space Launch Industry</i>	<i>Ozone Depletion, Climate Change</i>

ing activity is measured quantitatively through the proportion of laws, treaties, legal acts, parliamentary questions, or preparatory documents addressing this issue, among all other issues. Finally, public awareness is measured through a proxy metric: media coverage, using written press in a way analogous to before.

Additionally, the comparative study looks into the qualitative aspects of these policies, research, and press articles: specific topics addressed and their dynamic through time, causal relationships with historical events, and effectiveness of the interventions. The scope of the analysis is global (i.e. society is thought of as the international community and concerned countries), but geography-specific choices were made in the interest of data analysis, as described in the next section.

For any year  $y$ , and for each of the three metrics analyzed, the activity level  $r$  is defined as:

$$r(y) = \frac{\sum_{i=1}^M \sum_{j=1}^N a_{ij}(y)}{\sum_{i=1}^M \sum_{j=1}^{\infty} a_{ij}(y)} \quad (3.1)$$

With, for any of the three metrics analyzed:  $1 \leq i \leq M$  the categories of documents considered for the analysis (magazines, newspapers and wire feeds in the case of media coverage),  $1 \leq j \leq N$  covering all the sub-topics addressing the issue in question,  $a_{ij}(y)$  the number of documents published of the category  $i$  on the topic  $j$  during the year  $y$ .

### 3.3 Data gathering and processing

We relied on three databases to conduct this analysis: an academic research publication database, a newspaper database, and a legal database. A benchmark analysis of all publicly available and MIT-available databases was performed, and the choice was based on: geographic coverage, historical consistency, thematic coverage, neutrality of sources, and classification.

In order to make meaningful comparisons between time periods and across industries, the analysis was limited to the period 1990-2021. Before that, the reporting and digitization of all documents were sometimes scarce or biased towards certain sources. The scope of the analysis was limited to documents written in English. Overall, the analysis was conducted on a total of 463,630,586 news articles, 771,604 legal documents, and 10,836,398 academic publications over 30 years.

- **Research activity** The Web of Science database [50] from Clarivate was used. Were included in the search: research articles, abstracts, books, book chapters, and proceedings papers. Queries were built in an iterative process to make sure all aspects of the issue investigated were covered, but no other was included in the search. This process led to different query strategies depending on the industry and issue looked at. For instance, a query on research publications addressing the issue of emissions from the automotive industry was written as follows:

```
AB=((car* NEAR/3 emission*) OR (vehicle* NEAR/3 emission*)
OR (automotive* NEAR/3 emission*) OR (car* NEAR/3 pollution*)
OR (vehicle* NEAR/3 pollution*) OR (automotive* NEAR/3 pol-
lution*) OR (vehicle* NEAR/3 "exhaust gases") OR (car* NEAR/3
"air quality") OR (vehicle* NEAR/3 "climate change") OR (combus-
tion engine* NEAR/5 "climate change") OR (automotive NEAR/3
CO2) OR ("car exhaust" NEAR/3 particles) OR ("car exhaust" NEAR/3
particles))
```

- **Media coverage** The ProQuest database was used [51], which includes written press contents in the form of magazines, newspapers, and wire feeds. Social networks and other types of new media were not included in order not to bias the historical analyses which starts in 1990, before their apparition. For instance, a query on written press addressing the issue of emissions from launch vehicles was written as follows:

((("rocket launches" NEAR/2 emissions) OR (pollution NEAR/2 "rocket plumes") OR (rocket NEAR/1 emissions) OR (rockets NEAR/1 emissions) OR ("launch industry" NEAR/3 pollution) OR ("environmental impact" NEAR/3 rockets) OR ("ozone depletion" NEAR/5 "launch vehicles") OR ("atmospheric impact" NEAR/2 rocket) OR ("climate change" NEAR/5 "launch vehicle") OR ("rockets pollute") OR ("space tourism" NEAR/5 "pollution") OR ("space shuttle" NEAR/2 "pollution") OR ("space shuttle" NEAR/2 "ozone depletion") OR ("space tourism" NEAR/5 "emissions") OR ("space tourism" NEAR/5 "climate change"))) NOT ("pollution rockets" OR "emissions rocket" OR "emission rocket" OR "emissions will rocket"))

- **Policymaking activity** Comparatively to the two other metrics, the access to databases aggregating documents of different natures, from different types of institutions, in different geographies is very challenging. The choice was made to focus on the European Union, as they often precede national institutions in tackling environmental challenges (the legislation being then transposed at the national level for EU countries). Internationally, the EU also has a leading regulatory role, on environmental matters in particular, and made access to their data very easy. Therefore, we used the EUR-Lex database [52], including treaties, legal acts, consolidated texts, case-law, international agreements, preparatory documents, EFTA (European Free Trade Association) documents, lawmaking procedures, parliamentary questions, national transposition, national case-law, JURE (JURisdiction, Recognition, and Enforcement) case-law. For instance, a

query on legal documents addressing the issue of space debris was written as follows:

$$\text{DTS\_SUBDOM} = \text{ALL\_ALL AND } ((\text{TE} \sim \text{"space debris"}) \text{ OR } (\text{TE} \sim \text{"space junk"}) \text{ OR } (\text{TE} \sim \text{"orbital debris"}))$$

The activity level metrics were built using Equation 3.1, and the results are presented in the next section. Indispensable qualitative analyses were conducted in parallel by reading sample documents of the database searches (not just the volumes measured). Normalization was performed using 2016 data to compare the recent trends (with the exception of the analysis of policymaking activity in the satellite industry which used 2018 volumes for normalization as the volume vanishes for 2016). Notable influences of the Covid crisis on the results during the period 2019-2021 were investigated and reported in the plots below.

### 3.4 Comparative analysis

We start this analysis with an industry-by-industry presentation of our results for all three metrics. Then, we extend the analysis across industries: individual trends are analyzed, patterns are identified among societal reactions, along with sensitivities to diverse factors and contextual elements. Although inferring the existence of causal relationships between the trends observed is not possible from the plots alone, a thorough investigation of the content of the documents analyzed allows us to do so. For instance, we are able to connect peaks in academic research and policymaking activity to peaks in media coverage and known historical events.

Figure 3-1 shows the study's results for the automotive industry, on the issue of emissions. The sharp decrease over the period 2019-2020 in policymaking activity and media coverage on this issue is very likely associated with the COVID-19 crisis, not inherent to the automotive industry and its environmental impact. Regulatory efforts and media coverage were reoriented, right from the beginning of the crisis, from addressing environmental issues to managing the COVID-19 crisis.

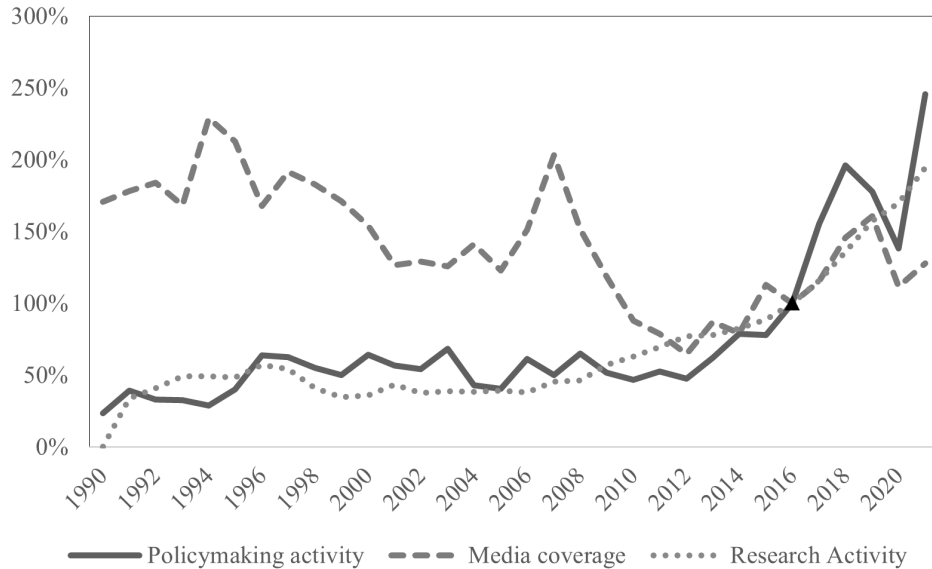


Figure 3-1: Societal response to the negative environmental externalities generated by the *automotive industry* during the period 1990-2021 (normalized activity levels, equated for 2016).

European emission standards on motor vehicles were progressively passed and upgraded between 1992 ("Euro 1") and 2014 ("Euro 6"), hence the long upwards trend. In 2018, following a UN report, EU countries announced an unprecedented cut to car emissions, followed by a plan for carbon neutrality in 2021, very visible in Figure 3-1 (activity level was doubled).

Since 1967 in the US, and especially in California, air pollution started being addressed by State and Federal regulators. It's only in 1990 however that the very influential Clean Air Act was implemented. The few years following the adoption of the Act saw a number of air pollution policies being implemented and made the news – visible on the plot, as the media coverage includes US-based activity, unlike the policymaking metric. In 2007, the US Supreme Court ruled in a very consequential decision that  $CO_2$  was considered a pollutant under the Clean Air Act (and therefore would be regulated by the Environmental Protection Agency), generating a sharp peak in media activity). In 2015, the Volkswagen emissions scandal (or "Dieselgate") occurred [46] and placed under the spotlight the issue of air pollution from car emissions. Study of the content from 2015 media articles and onward shows that this

scandal is the main driver behind the growth of media coverage in 2015, which would continue over the next few years due to subsequent consequences of this affair in the public space, coupled with the overall rise in environmental awareness.

Academic research activity on car emissions shows a very smooth increase over the 30-year period, indicating a low reactivity to historical events and the influence of deeper societal factors. Among these factors is the growing general level of environmental awareness, leading to investments in research and development. Although the global trend is very smooth, sub-topics accounted for in this metric do evolve with time and respond, with relative inertia, to contextual events.

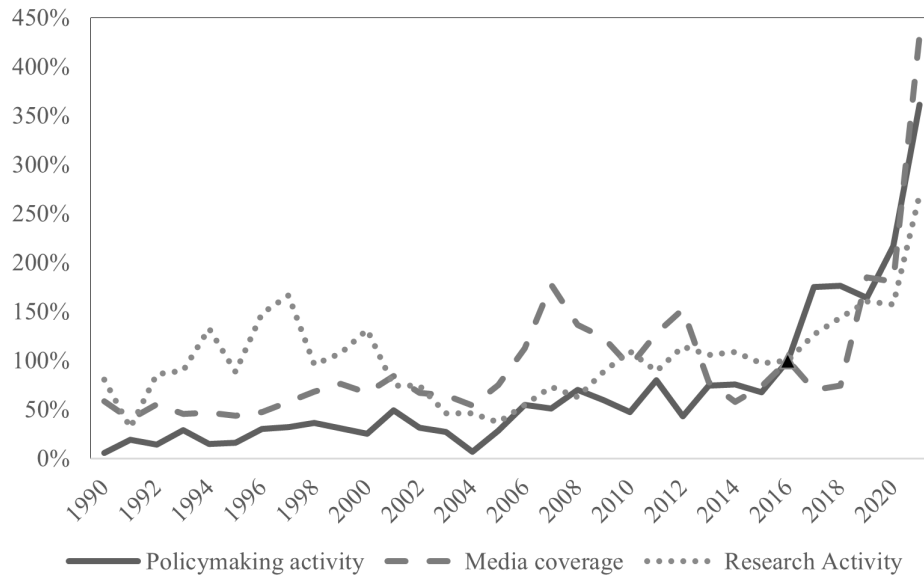


Figure 3-2: Societal response to the negative environmental externalities generated by the *aviation industry* during the period 1990-2021 (normalized activity levels, equated for 2016).

Figure 3-2 shows the societal response to the atmospheric pollution generated by the aviation industry. Although the environmental impact of this industry was a known concern since a couple decades back, it's only in the past decade that awareness levels started rising. Aviation's carbon footprint has naturally appeared as a topic for EU regulatory work much later than car emissions. In 2017, it was even decided that commercial flights would not be included in carbon emission controls, after discussions in the EU (hence a policymaking activity peak, which wasn't followed by regulatory

action). It's only in 2021, as airlines and aircraft manufacturers were benefiting from COVID-19 help plans, that the Commission proposed a tax on fuel for flights within the EU. This explains the remarkably sharp peak in policymaking activity last year (+260% activity level compared to 2016).

In terms of media coverage, 2018 was marked by the apparition of the "flight shame" movement (*flygskam* in Swedish), which would go with a sudden peak of attention on this issue (+370 points between 2018 and 2021). This was just before the Commission acted on the issue, precipitated by the COVID-19 recovery plan. The noticeable spike in media coverage in 2007 is associated with the International Civil Aviation Organization (ICAO) presenting guidelines endorsing a mechanism of emissions trading for aviation.

Post-COVID investment plans seem to have accelerated the research pace (+110 points) on sustainable fuels, hydrogen-powered aircraft, and atmospheric impact assessments. However, academic research had been following a pre-existing upward trend, much smoother than the other two curves, indicating a lower sensitivity to momentary context.

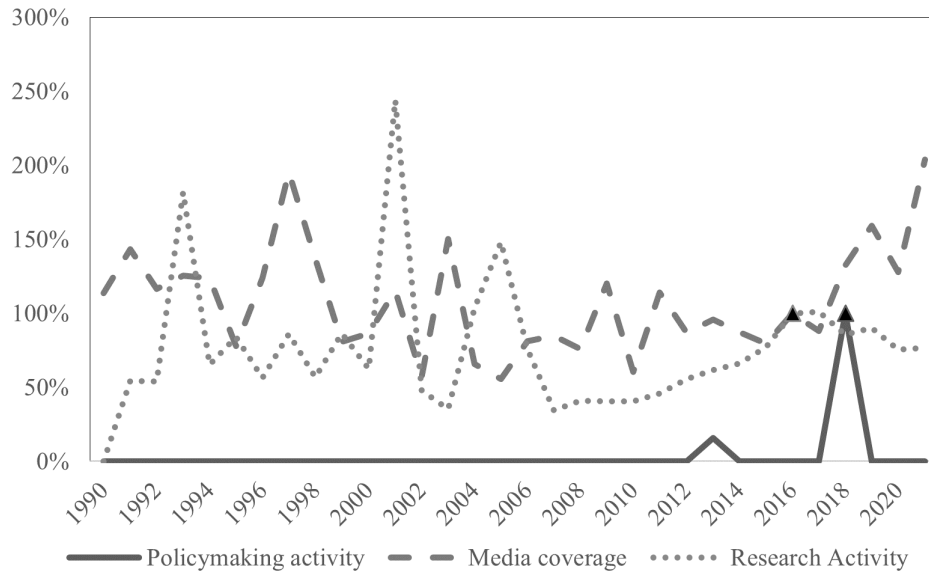


Figure 3-3: Societal response to the negative environmental externalities generated by the *satellite industry* during the period 1990-2021 (normalized activity levels, equated for 2016).

Figure 3-3 shows the societal response to the issue of space debris generated by the satellite industry. For all three metrics measured, the activity data is considerably more scarce on the space debris relative to the previous two issues. This was expected considering the relative size of the industries, and the current visibility of the issues. While space debris seem to have become a more installed topic since 2015, before that media coverage used to be only triggered by isolated events. In 1997 for instance, a person was for the first time hit by a space debris. Peaks are also observed due to isolated ASAT (Anti-SATellite) tests generating debris: in 2007 from China, 2019 from India, 2021 from Russia, although the US ASAT does not appear. This is probably a sign that, because our scope only encompasses documents written in English, there is an expected bias towards Western countries. The US ASAT test was not perceived as a threat compared to Russia (USSR's) and China's more recently, hence generating a lower level of media coverage. The 2003 peak is an alias due to the Columbia space shuttle incident, generating non-orbital "space debris". In 2009, two communications satellites accidentally collided, generating a significant cloud of debris, and important media coverage. Similarly to the disintegration of a Long March booster in 2000. During the following year, the US would issue new practices for orbital debris mitigation, generating attention.

In terms of policymaking, within EU institutions, the first significant mentions of space debris and mitigation plans only start to appear in 2018 as part of the new EU Space Programme. However, although it is not measured here, space debris have been the topic of few additional national guidelines and policy work in several countries [53].

Academic research activity follows for space debris a pattern very different from the previous ones. Because of the very low volume of research, the small variable component triggered by local events is very visible. Since 2007, space debris seem to have become a more installed topic in academic research – as it would become for media coverage soon after.

Figure 3-4 shows two main periods of activity on the issue of atmospheric emissions from the space launch industry: 1990-2000, and 2016 until today. The first one is

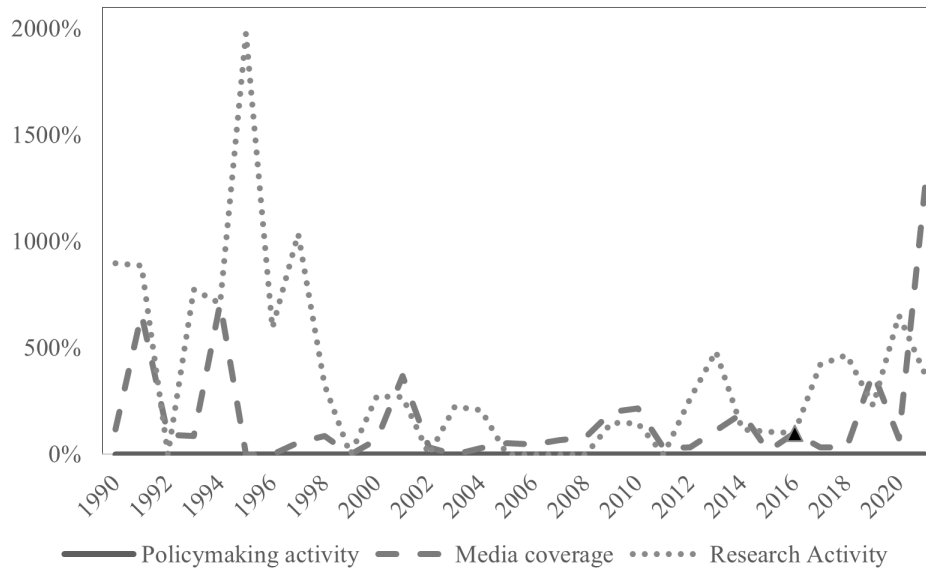


Figure 3-4: Societal response to the negative environmental externalities generated by the *space launch industry* during the period 1990-2021 (normalized activity levels, equated for 2016).

associated with the Space Shuttle, whose solid rocket boosters generated important concerns of contribution to ozone depletion at the time. The second period is driven by the renewed visibility of the space industry (the "New Space"), and the rise in the general level of environmental awareness. Levels of media coverage skyrocket in 2021 (+1300% in one year) due to criticism over the environmental impact of space tourism.

### 3.5 Current policy response

Like other forms of atmospheric emissions, the fact that rocket emissions are not contained by national borders motivates the need for international coordination in order to effectively regulate them. To date, there is no international regulatory policy that directly addresses the atmospheric impact of rocket emissions. However, the Montreal Protocol and the Kyoto Protocol – two existing "societal response" frameworks to regulate global emissions – can be compared for their relative effectiveness and applicability to rocket emissions to understand what challenges and opportunities for

regulation may exist.

While the Montreal Protocol provides a successful example of an internationally accepted and enforced response to harmful emissions to the atmosphere, its direct applications to rocket emissions are lacking, as it addresses ozone-depleting compounds emitted on the ground [11]. The Kyoto Protocol, on the other hand, which addresses the emissions of greenhouse gasses, has not been widely implemented. Comparing these two policies provides an interesting case study in regulating emissions impacting the environment on a global scale: while the Montreal Protocol has been highly effective, it was enacted without a unanimous scientific consensus about the impacts and level of mitigation needed to address ozone depletion, partially due to the perceived immediate threat that ozone depletion would have [54]. On the other hand, despite widespread scientific agreement on the effects of greenhouse gas emissions and required reductions to meet climate targets laid out by the IPCC, national-level regulations to curb greenhouse gas emissions in line with the Kyoto Protocol remain largely unimplemented. The geopolitical implications of acting on partially-replaceable ozone-depleting substances were far less harmful to national economies than acting effectively on climate change.

At national and local levels, there are very few environmental policies that assess or mitigate the environmental impacts of emissions from space launches. In France, a 2009 decree requires space vehicle operators to undergo an environmental assessment prior to receiving authorization to launch [55]. In the U.S. – which in 2020 accounted for  $\sim 40\%$  of global space launches [56] – existing policies are limited to the general mandates of the Environmental Protection Agency (EPA), which requires assessment of all emissions sources and compliance with the standards of the Clean Air Act, and the Federal Aviation Administration (FAA), which requires launch vehicles and spaceports to undertake an environmental review before they receive a license to operate. Under the Clean Air Act, the EPA sets emissions standards for atmospheric pollutants based on whether the source is stationary (more stringent standards) or mobile (less stringent standards). Previous determinations by the EPA have classified rocket launches as mobile sources, and no rulings have been made about the specific

pollutant standards which apply to rocket engines [57].

Recent filings for the licensing of Starship/ Super Heavy rocket launches in Texas reflect the current position of U.S. regulatory agencies and industry that the atmospheric impacts of space launch are negligible (see Appendix A). In Starship's environmental assessment, it was noted that launch emissions are anticipated to be well below air quality standards for all major pollutants and that in regards to evaluating the climate impact of launch, there are currently no established methods supported by the FAA to evaluate the significance of greenhouse gas emissions from rocket launches [58].

"The FAA has not established a significance threshold for climate, nor has the FAA identified specific factors to consider in making a significance determination for GHG emissions. There are currently no accepted methods of determining significance applicable to commercial space launch projects given the small percentage of global GHG emissions they contribute. (A-2)

The filings estimated the greenhouse gas emissions of Starship/ Super Heavy operations would be around 47,522 metric tons per year assuming 5 Super Heavy launches, and noted that this is negligible in comparison with the total U.S. annual greenhouse gas emissions, which at the time of filing were around  $5 \times 10^7$  metric tons per year [58].

"The GHG emissions associated with the estimated emissions for the Proposed Action is compared to global and U.S. emissions [...]. The estimated  $CO_2$  emissions from annual operations of the Starship/Super Heavy Program are significantly less than the total GHG emissions generated by the United States in 2018 and the total  $CO_2$  emissions generated worldwide [...]" (A-3)

As the U.S. is currently the largest emitter of greenhouse gasses globally and space launch represents a notably small industry, this comparison may not be the most apt to assess either the relative or absolute future impacts of rocket launches.

In addition to that, the way emissions are accounted for does not factor in the specific altitude of emissions.

" $CO_2$ , and to a lesser extent,  $CH_4$  and  $N_2O$ , are products of combustion and are generated from stationary combustion sources as well as vehicles. The following formula is used to calculate the Carbon Dioxide Equivalent ( $CO_2e$ ).  $CO_2e = (CO_2 \times 1) + (CH_4 \times 28) + (N_2O \times 265)$ " (A-1)

"GHG emissions for this project are considered globally since climate change is a global issue. This means GHG emissions are considered at all altitudes for a Starship/Super Heavy launch and for all proposed construction activities." (A-2)

In this calculation, emissions on the launchpad, in the troposphere, in the stratosphere and above contribute equally to the atmospheric impact, which is very incorrect as discussed in Chapter 2. For this reason, and following a call for public comments on the Draft Programmatic Environmental Assessment, we made an oral comment asking for FAA's response on these different points (see A-4). The release date for FAA's decision and replies to all comments has been delayed repeatedly since December 2021, and is now expected for a date ulterior to the publication of this present work.

## **3.6 Discussion and perspectives for the space launch industry**

The comparative analysis presented above for all industries (see also Tables 3.3, 3.4, 3.5, 3.2), combined with our assessment of the state of the rocket emissions' impact and the level of societal response to it, informs us of the ability of society to anticipate this likely problematic situation in the future, and on its capacity to act effectively on it.

Our results suggest that societal response in the form of research activity (Figure 3-5 on such topics is characterized by longer, smoother trends, and low reactivity

to momentary events and context. This can be associated with significant inertia in research programs, from a macroscopic standpoint (inside a same research area, however, traction on sub-topics can evolve rapidly with time ). Media coverage (Figure 3-6), as expected, is much more reactive to the societal environment, and can be triggered by local events. Policymaking activity (Figure 3-7) is also relatively reactive to the societal context, but with a threshold effect. It requires a context of pre-existing "background activity" on the topic, and then ideally triggered by momentary events, but the latter is not enough in itself to trigger policy response. Policymaking activity only starts quite late compared to the research activity and media coverage patterns. It is, however, the one, among the three metrics, that can lead to effective action on the issue at hand (the two other are only enablers).

CAGR (%)	Media coverage	Research activity	Policymaking activity
2019-2021 (2y)	81.3	28.1	-
2016-2021 (5y)	65.8	30.2	-
1991-2021 (30y)	8.2	-2.9	-

Table 3.2: Compound Annual Growth Rate of the activity level on each three societal response metrics for the space launch industry, for the past 2 years, five years, and thirty years

CAGR (%)	Media coverage	Research activity	Policymaking activity
2019-2021 (2y)	-10.7	11.2	17.5
2016-2021 (5y)	5.0	14.2	19.7
1991-2021 (30y)	-1.0	6.2	8.1

Table 3.3: Compound Annual Growth Rate of the activity level on each three societal response metrics for the automotive industry, for the past 2 years, five years, and thirty years

CAGR (%)	Media coverage	Research activity	Policymaking activity
2019-2021 (2y)	52.8	29.6	48.5
2016-2021 (5y)	34.0	21.9	29.3
1991-2021 (30y)	6.9	4.1	14.7

Table 3.4: Compound Annual Growth Rate of the activity level on each three societal response metrics for the aviation industry, for the past 2 years, five years, and thirty years

CAGR (%)	Media coverage	Research activity	Policymaking activity
2019-2021 (2y)	13.2	-7.8	-
2016-2021 (5y)	15.3	-5.2	-
1991-2021 (30y)	2.0	1.2	-

Table 3.5: Compound Annual Growth Rate of the activity level on each three societal response metrics for the satellite industry, for the past 2 years, five years, and thirty years

The issue of rocket emissions in the launch industry is characterized by currently low levels of academic research activity and isn't prone to impactful events compared to the automotive industry or the satellite industry (city air pollution peaks or satellite collisions for instance). For this reason, it will hardly trigger the natural response patterns observed in other industries. In particular, its contribution to climate change – very much unknown in magnitude – cannot be measured directly.

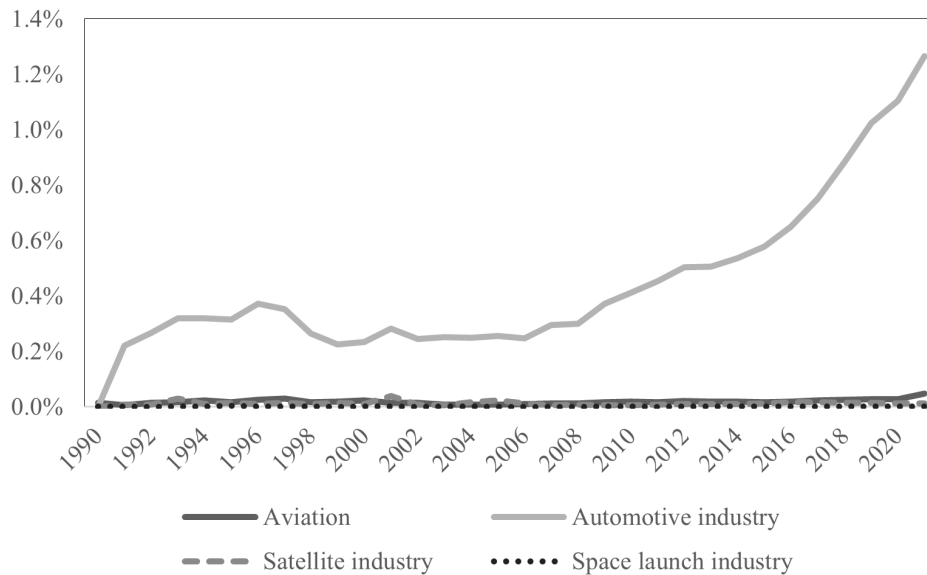


Figure 3-5: Research activity level for all four {industry, negative environmental externality} pairs under study, during the period 1990-2021 (independently normalized activity levels)

A systems dynamics model of the phenomenon observed for all four {industry, negative environmental externality} pairs, each at different stages in the societal response pattern, is shown Figure 3-8.

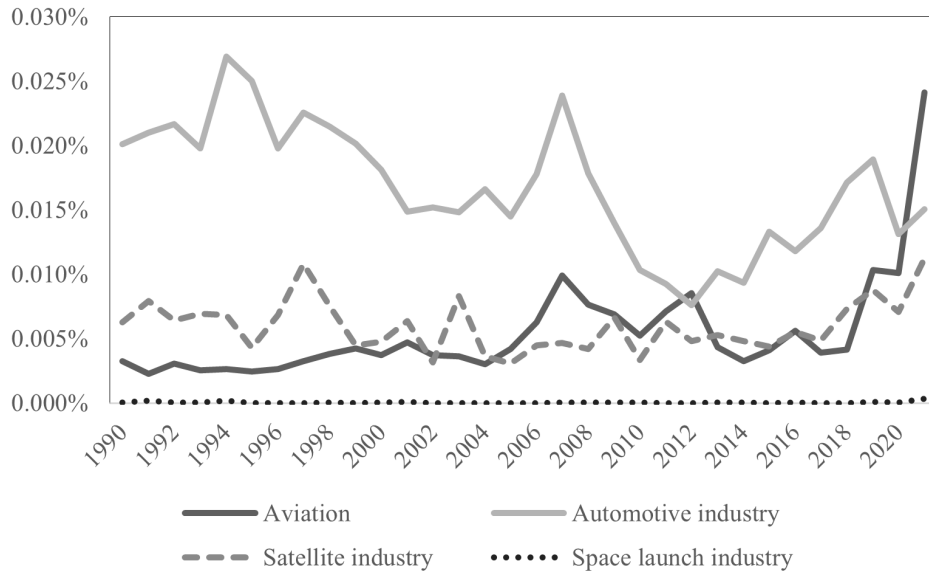


Figure 3-6: Level of media coverage for all four {industry, negative environmental externality} pairs under study, during the period 1990-2021 (independently normalized activity levels)

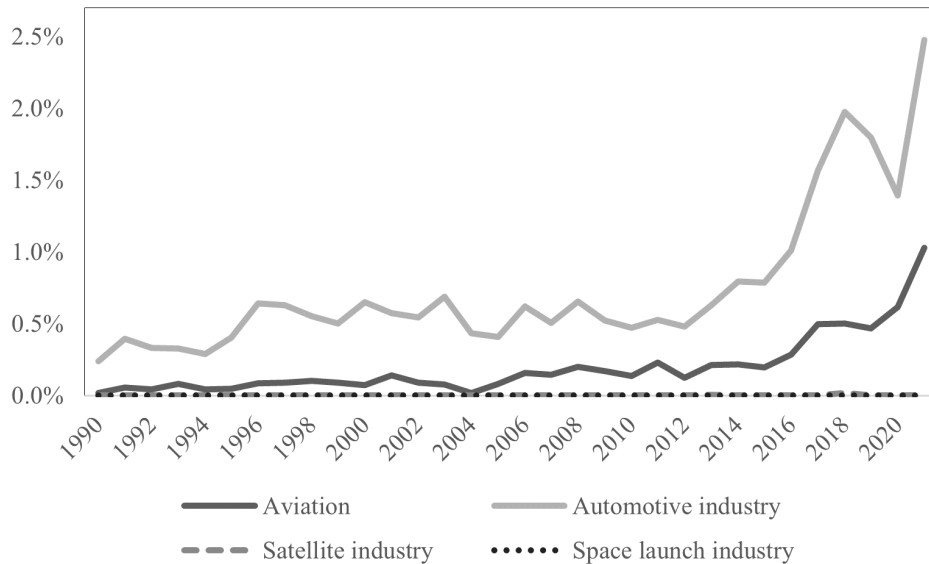


Figure 3-7: Policymaking activity level for all four {industry, negative environmental externality} pairs under study, during the period 1990-2021 (independently normalized activity levels)

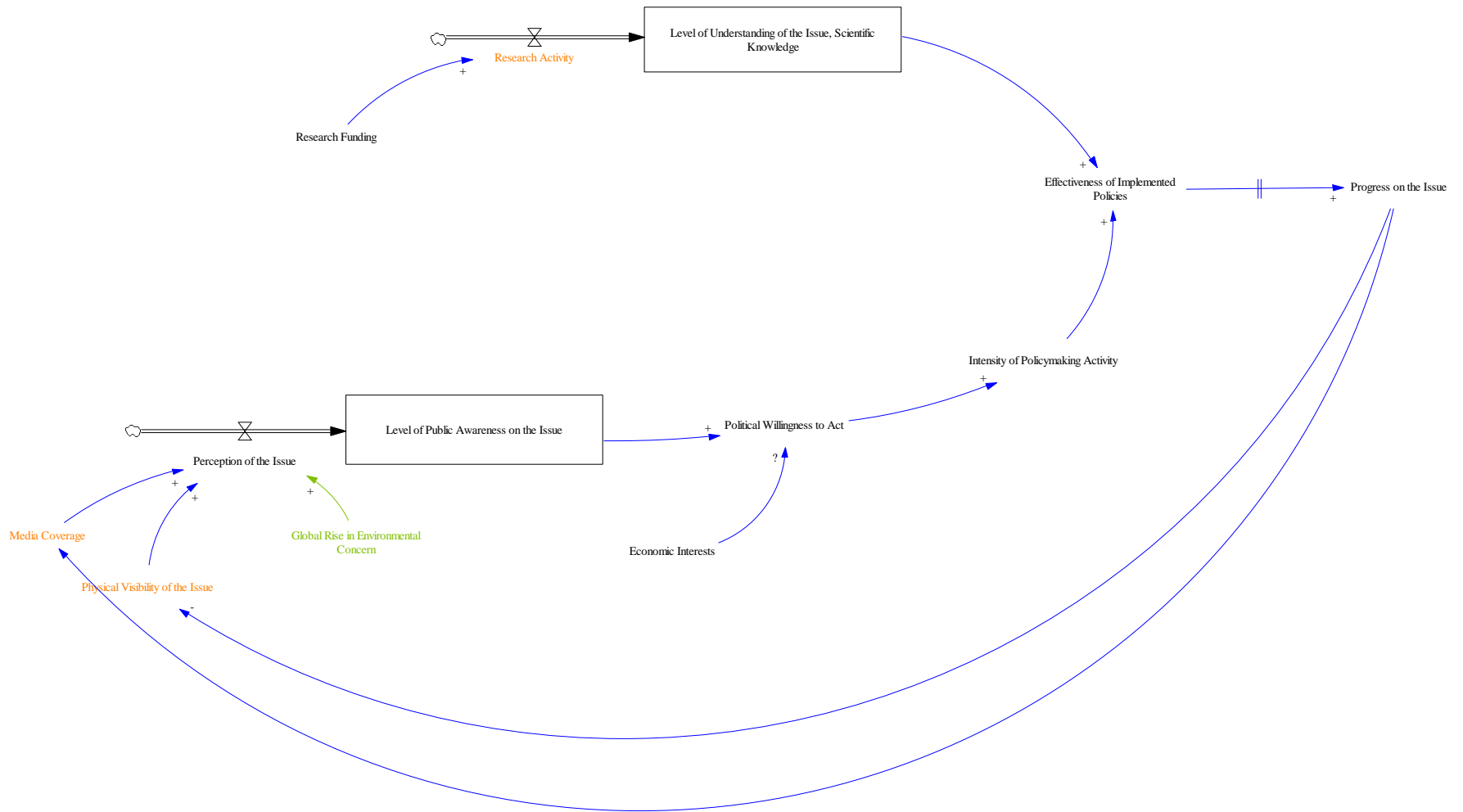


Figure 3-8: Systems dynamics modeling of the observed societal response behavior to negative environmental externalities generated by human activities. Variables in orange show the metrics measured as part of this analysis. Diagram generated on Vensim.

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# Chapter 4

## Paths forward

In a context of growing commitment towards sustainability for all human activities [59], the space launch industry is facing important challenges ahead. The findings presented previously show the expected sharp increase in negative environmental externalities from space launches as well as the lack of societal response and preparedness to mitigate them (general lack of academic research, policymaking activity, and involvement from launch vehicle manufacturers). The path forward on this matter will be defined by the nature of the solutions available to reduce the impact and the alternative ways to enforce these solutions effectively.

### 4.1 Launch vehicle design

Until today, and for the foreseeable future, the only way to reach orbit and beyond is through rockets powered by chemical propulsion. Any strategy to ensure a more sustainable future for the space launch involves the development of rocket engines with improved environmental performance.

The design of launch vehicles has been consistently driven by mission performance, cost and reliability so far. Initial guidance, although evident, is that environmental impact and sustainability will have to become key considerations in rocket design and manufacturing. The diversity in rockets' environmental impacts resulting from their diversity in designs demonstrates that there exists a tradespace on that matter,

especially regarding propellant choices.

SRMs' harmful emissions of chlorine and alumina particles are associated with ozone depletion, radiative forcing, and local ground impacts through acid rains for instance. These effects should lead to a reduced role of these boosters in the architecture of future launchers, although they will still be used in the future by SLS, Ariane 6, Vulcan Centaur, or Long March 11. LOx/Kerosene engines, because of their emission of soot particles and their radiative forcing effect, should also be carefully considered. They are currently among the most popular rocket fuels in the US, Russia, and China. Hypergolic rocket fuels (based on nitrous oxide and UDMH – unsymmetrical dimethylhydrazine) are extremely toxic for local ecosystems, and for human beings. Launch vehicle manufacturers in America and Europe have already moved away from it, Russia (a long-time user) seems to be transitioning as well, but China still relies on hypergolic propellants heavily so far. LOx/Hydrogen rocket engines are so far the cleanest technology to have flown to orbit. This is the propulsion technology to be used soon on Ariane 6, SLS, and Vulcan Centaur.

A growing number of launch vehicle manufacturers have started including sustainability considerations in the design of their launchers. In Europe, ArianeGroup has investigated the environmental impact of their Ariane 5 and future Ariane 6 launchers, and included it as a requirement in the development of the Prometheus engine. Startups such as Skyrora and Orbex have demonstrated efforts to reduce the environmental impact of their propellants (kerosene-based) [60, 61], in particular from their manufacturing. Finally, the recent development of LOx/Methane rocket engines for the next generation of launch vehicles (Starship, Rocket Lab's Neutron, New Glenn, Vulcan Centaur, Ariane Next) may prove beneficial in terms of atmospheric emissions (water, and  $CO_2$  and limited soot as main combustion products), although much more research is needed on that end, especially on life cycle aspects.

Multidisciplinary Design Optimization (MDO) approaches could reveal instrumental in making this shift to environmentally performing design choices, for their ability to handle particularly well systems interactions and multiobjective analysis with a multitude of disciplines involved. See Figure 4-1 for an MDO model adapted

to such an approach, and Figure 4-2 for the type of analyses it could enable.

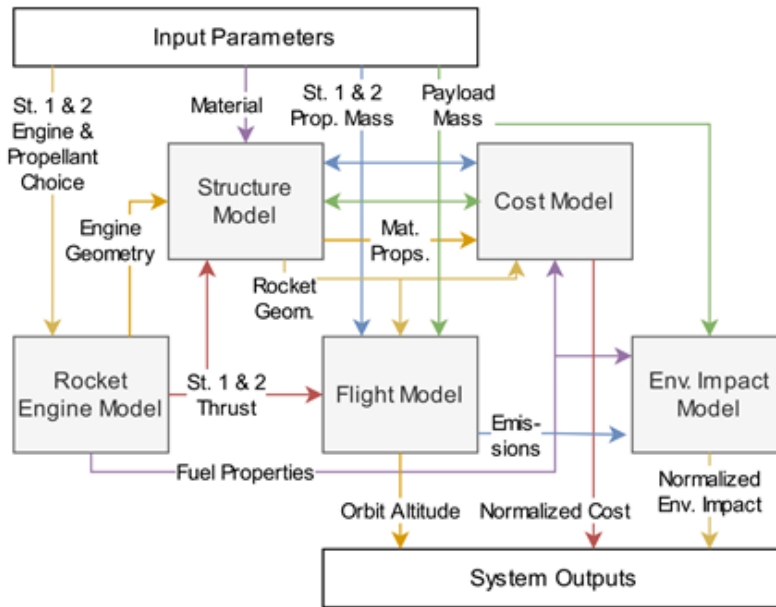


Figure 4-1: Diagram of a proposed MDO model for the design of launch vehicles (Objectives: Cost, Performance, Environmental Impact) (Source: MIT 16.888 – Benjamin Yu, Justine Schultz, Lyle Regenwetter)

## 4.2 Impact assessment

The development of new environmental impact assessment methodologies dedicated to launchers, and their diffusion in the industry, will be central to this strategy. This will also enable a number of cost-benefit analyses for a number of missions involving launch vehicles (Figure 4-3): the impact of deploying and maintaining LEO constellations, the Artemis program, Earth-to-Earth transportation on SpaceX’s Starship, space tourism, on-orbit servicing and assembly (OSAM), as well as in-situ resource utilization (ISRU) of materials on the Moon and on Mars.

### 4.2.1 Methodological and empirical gaps

Existing techniques are hardly applicable because of the unique environments in which launch vehicles operate, and because of the type of emissions they generate.

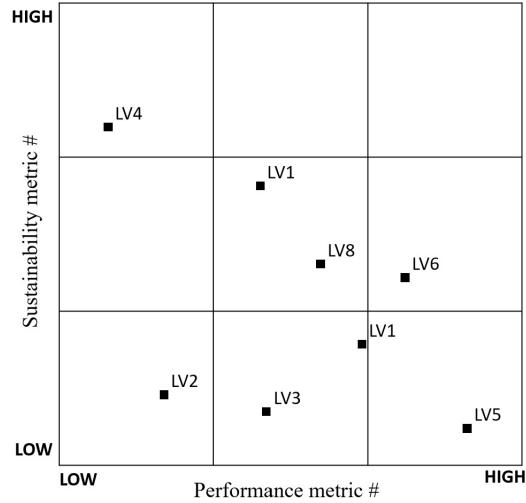


Figure 4-2: Impact matrix template for existing launch vehicles and potential new design choices – results accessible through MDO analysis

Life Cycle Assessments (LCAs), which constitute a very recent practice in the space industry – especially in Europe [16] – will have to become widely used so the environmental performance of launch vehicles can durably improve. This will avoid typical burden-shifting phenomena as LCAs allow for accounting for all impacts from the drawing board until the launch and disposal of the systems. These will be critical too to assess the environmental benefits of reusable rocket stages for the next fleet of launch vehicles.

There is also a number of more fundamental gaps regarding the science of rocket emissions. As highlighted in Chapter 2, almost all papers recently published on the topic highlight this urgent need for more study of the nature and magnitude of ozone depletion and radiative forcing effects [11, 13, 62, 25, 12]. This research will both necessitate in situ measurements and improved atmospheric modeling.

### 4.2.2 Sustainability index

If environmental performance was to become a competitive advantage in the launch services market, launch vehicle manufacturers would naturally be incentivized to opt for sustainable designs – especially regarding propellant and engine choices. The development of a sustainability index for launch vehicles could be instrumental for

this purpose.

This index, developed by a multilateral body of scientists, engineers, and industry representatives, should include measurable metrics on all relevant aspects of the rocket's life cycle, not restricted to atmospheric emissions to avoid burden shifting. This solution could lead to a purely market-based approach, but also be a basis for future international regulations.

This would also enable actors in the space industry (clients of launch vehicle manufacturers, space agencies, etc.) to evaluate the impact of their activities both a priori and a posteriori. This system shall also include, in addition to environmental impacts, the mission characteristics such as payload masses and orbits, in order to assess the 'efficiency' of these launches. Also, this research will be conducted at the level of the global fleet of launch vehicles, enabling comparisons. Figure 4-4 presents the framework behind the conception of such a sustainability index, and Figure 4-5 the society-level mechanisms that would make it effective.



### **LEO Constellations**

OneWeb, Starlink, Kuiper, Guowang...

Evaluation of the impact of launches required for the deployment and maintenance of LEO communications and EO constellations with thousands of satellites. Mitigation strategies.



### **Cost-Benefit Analysis of Earth Science Missions**

NOAA, ESA...

Environmental cost-benefit analysis of earth science satellite missions.



### **Earth-to-Earth Flights**

SpaceX

Impact of stratospheric emissions from Earth-to-Earth transportations (civil or military logistics, business...).



### **Space Tourism**

Virgin Galactic, SpaceX...

Impact of stratospheric emissions from the nascent space tourism industry.



### **Moon/Mars Human Spaceflight Program**

Artemis

Impact of stratospheric emissions from SLS and Starship launches required for the logistics of the Artemis program.

Figure 4-3: Applications: case studies, future scenarios. Image sources – 1: National Geographic 2: OneWeb 3: SpaceX 4: Virgin Galactic 5: NASA

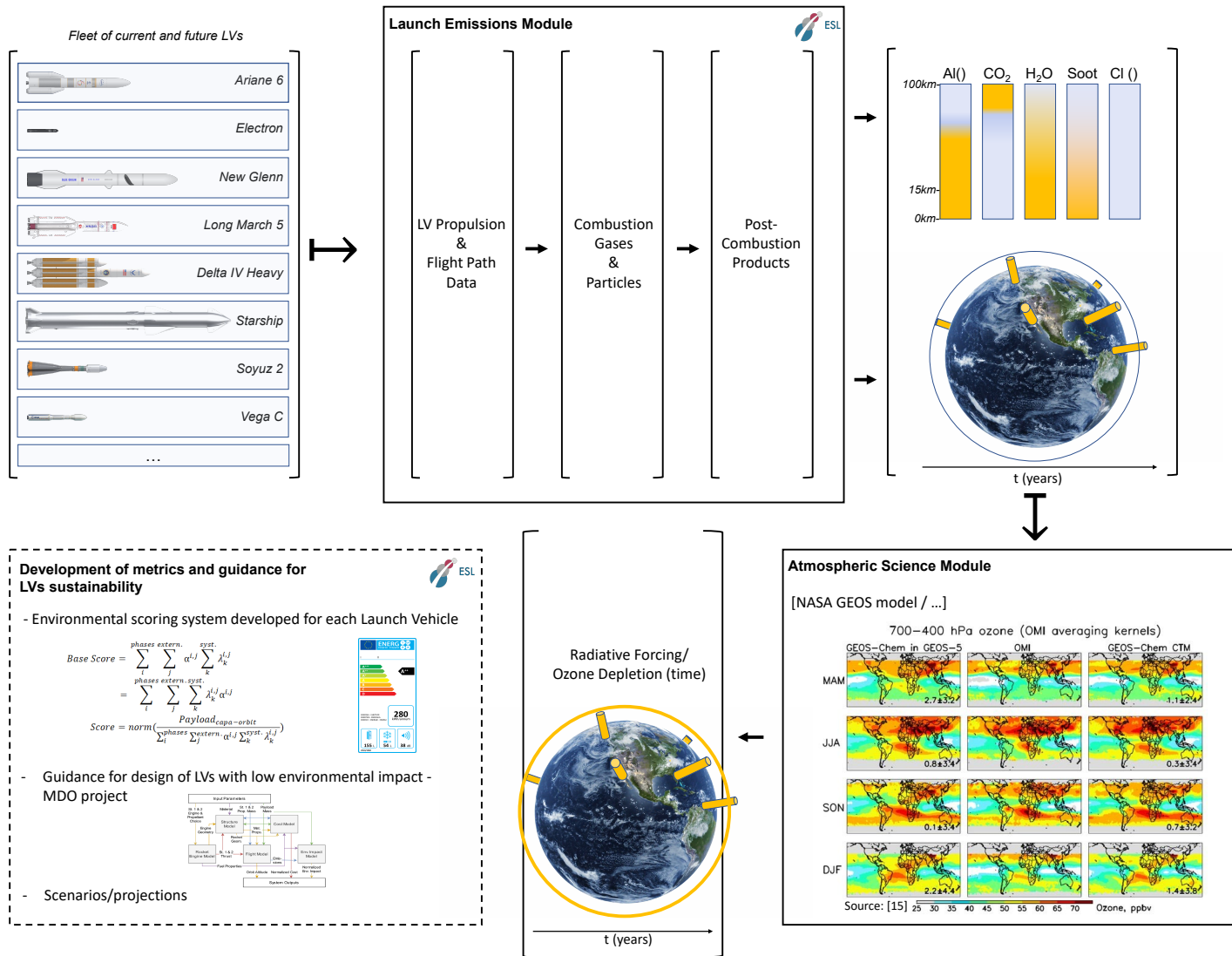


Figure 4-4: Framework for the conception of a sustainability index assessing the environmental impact of launch vehicles – focus on atmospheric emissions here.

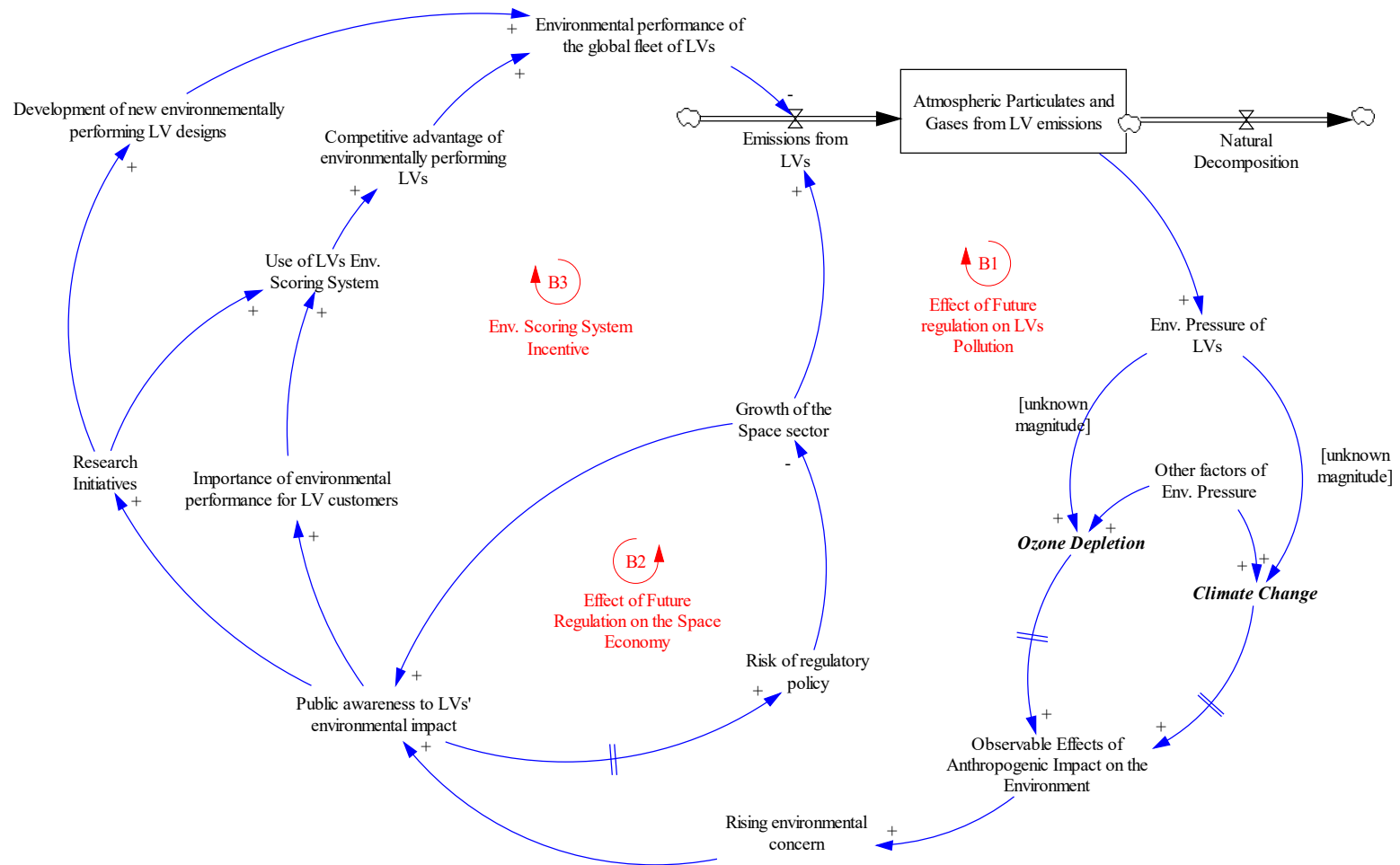


Figure 4-5: Systems dynamics representation of the effects of the introduction of a sustainable rating system for launch vehicles to address the negative environmental externalities from the launch industry, and societal response to it.

## 4.3 Policymaking

### 4.3.1 Regulatory challenges

Rocket emissions fall into a category of environmental impact that may be particularly difficult to regulate for at least three reasons. First, there are many gaps in the scientific understanding of rocket launch and reentry emissions and a lack of appropriate metrics to characterize their exact environmental impact. Second, despite the fact that rocket launches do produce compounds that are known to affect the atmosphere in complex ways, they lack an immediate, visible, and salient threat in the public consciousness. And finally, they occur in the atmosphere, which is a global commons.

Effective regulation and mitigation of any harmful effects of spacecraft launch and reentry emissions will ultimately require a baseline understanding of the existing issue and the potential impacts that may result from increased number and frequency of rocket launches. Whether binding legislation or voluntary norms are enacted, specific metrics will need to be developed that identify atmospheric and climate variables relevant to spacecraft launch and reentry and allow different spacecraft designs to be quantitatively evaluated and compared.

As described in detail in previous sections of this paper, spacecraft launch produces chemical and particulate matter which is known to affect the atmosphere in complex ways - and evaluating emissions based on existing metrics such as carbon footprint may underestimate or mischaracterize the true impact [13]. Addressing the uncertainty in quantifying environmental consequences of rockets is an additional challenge and one that must be accounted for in developing metrics.

As the inaction around the Kyoto Protocol illustrates, even once a scientific consensus on an issue has been established, translating scientific understanding to policy can remain a significant challenge. To be actionable, scientific understanding must be presented in a way that is credible, salient, and legitimate to the public and policymakers [63]. Currently, the issue of spacecraft launch and reentry lacks the critical mass of credible and legitimate scientific assessment needed to come to a clear and

accepted understanding of the complex consequences of rocket emissions.

Efforts to address emissions also may be faced with the lack of a salient motivating factor to act. As Ross and Vedita note, with the relative infrequency of launches historically and the lack of any clear and visible indicator of negative impacts resulting from the status quo, governments and regulatory agencies have been operating under the implicit assumption that spacecraft emissions pose an acceptable or negligible environmental risk and will continue to do so [11]. This perception of the risk as negligible is not based on scientific assessment that all chemical components of spacecraft emissions are fundamentally harmless in the atmosphere - but rather is based on the assessment that they are small by volume, particularly compared to emissions from other sources. In addition, this assumption does not account for the future growth of spacecraft launch and reentry, nor does it take into account the increasing difficulty of regulating the industry in the future in the event that spacecraft design choices are widely adopted and become “locked-in” before full comparative assessment of the environmental impacts of different design choices have been done.

The atmosphere is a global commons, where emissions that are produced locally are able to mix beyond national borders and broader issues are the result of collective actions taken at smaller scales. As such, regulating any aspect of it faces unique challenges. Even in the event that there is sufficient political will at a national or local level to regulate spacecraft emissions, policies that regulate or incentivize participation internationally are critical to maintaining a global commons [64]. The “polycentric” nature of action – meaning regulatory or market approaches from both the top-down and bottom-up – that is required to effectively manage issues in the global commons means that any proposed change to the status quo of spacecraft emissions will have to appropriately motivate or require individual launch services providers to take actions that align with the interests of a large and diffuse community. Without strong and enforceable legislation, this may occur through design choices that, for example, reduce emissions at reduced cost to the operators – thereby aligning their individual interests with the collective.

### 4.3.2 Policy Alternatives

Although individual initiatives from countries and manufacturers will be valuable to develop tools and frameworks, effective action on this topic will indubitably require global action. Based on the findings of the prior section, regulatory alternatives can be explored as well as market-based solutions.

We discussed how challenging implementing regulation on this matter could be, due to the lack of scientific data, due to its lack of visibility and apparent urgency, and due to the imperative need for global coordination. However, the increasing level of public awareness on general environmental topics, combined with the renewed exposure of the space launch industry, could very soon change this reality and create a sense of urgency. This regulatory approach could also benefit from the already existing diplomatic and scientific networks developed around climate action. Furthermore, our comparative analysis of the Montreal and Kyoto Protocols suggest that the present lack of science should not prevent discussions from taking place, to start identifying viable solutions for all stakeholders.

Then comes the question of the type of regulation that would be the most effective and realistically applicable at this scale. Taxes on rocket emissions could be considered based on the purpose of a launch (tourism, weather monitoring satellite, etc.), as was proposed in the U.S. in 2021 to target space tourism [14, 15]. Economic effects should however be expected where these policies are adopted, with losses of attractiveness to launch services providers. Additionally, the line being very thin between some space tourism missions and other missions with a public benefit, defining the purpose of a trip will be challenging. Bans on specific types of propellants (for their harmful combustion products) could also be considered as part of the licensing process for launches. This may reveal challenging, as some countries' launch industries rely on unique propulsion technologies, and ultimately require stronger scientific evidence. On a related issue, the UN adopted in 2022 a provision to phase out mercury (a heavy metal which is highly toxic to humans) used for in-space propulsion, out of concern that it would then return to Earth's surface [65].

The sustainability index mentioned earlier could serve as a market-based mechanism to push towards sustainable options through competitive advantage, being a legitimate reference on which to build comparisons. It could also be a basis for future regulations. Cap-and-trade policies constitute another market-based option, where emissions would be limited by company or country, and could be traded, similarly to the European Union's Emissions Trading System solution since 2005.

# Chapter 5

## Conclusions

The space economy is expected to continue growing at a fast pace over the next two decades, likely reaching the trillion-dollar mark around 2035. The launch industry would then quadruple in volume of annual launches and its environmental impact most probably soar if no strategy is implemented to mitigate it.

Atmospheric emissions from space launches are highly dependent on the design choices made on the launch vehicle, at the forefront of which are the rocket engine and propellant mix. Although literature in this area is still relatively scarce and magnitudes of the impacts remain to be precised, specific combustion products have been identified as consequential on higher atmosphere chemistry. Black carbon, alumina particles, chlorine, and nitrogen oxides are the most prominent of these. Propellants associated with these emissions, such as solid fuels, hypergolic rocket fuels, and LOx/Kerosene engines should be used with restraint. LOx/Hydrogen is in comparison relatively harmless, and LOx/Methane emissions still need to be thoroughly studied, especially on life cycle aspects.

International treaties do not presently address rocket emissions. Only general environmental regulations, mainly at the national and local levels, exist. This is mainly due to the perception of this impact as being minor, to the traditionally strategic nature of the space industry, and to the typical difficulties of addressing 'Commons' problems. Results of the comparative analysis of societal responses to various negative environmental externalities suggest that the current response is very

low, especially in terms of policymaking activity. The recent peak in media coverage and research activity take-off could be precursors of future regulations, but go with significant inertia as in all industries investigated. Future work should investigate the geographic discrepancies in societal response, especially between established space powers and emerging space-faring nations.

To avoid future impacts harmful to societal well-being, sustainability will have to become a key consideration in rocket design and manufacturing. This is a critical time for implementing these solutions, as the number of new rocket designs being developed has never been higher, and as technological choices made today will define the impact of the future fleet of launch vehicles. Market-based incentivization of launch vehicle manufacturers towards sustainable designs could prove very effective, therefore future work should focus on methodologies and metrics development to better assess the environmental impact of launch vehicles.

## Appendix A

Selected pages from FAA's Draft  
Programmatic Environmental  
Assessment for the SpaceX  
Starship/Super Heavy Launch  
Vehicle in Boca Chica

an exceedance of a NAAQS for any criteria pollutant. Emissions from aircraft being re-routed would occur above 3,000 feet (the mixing layer) and thus would not affect ambient air quality.

In summary, the Proposed Action is not expected to result in significant impacts to air quality.

### 3.3.5 Mitigation and Monitoring

The FAA would ensure that SpaceX would implement the following measures to minimize impacts on air quality.

- Periodic water spraying to control particulates and fugitive dust
- BMPs such as minimal idling of engines, watering of soils to be disturbed, and use of low volatility coatings.
- Compliance with TCEQ's authorization under the Oil and Gas Standard Permit, including adherence to any permit conditions.

## 3.4 Climate

### 3.4.1 Definition of Resource and Regulatory Setting

Climate change is a global phenomenon that can have local impacts. Scientific measurements show that Earth's climate is warming, with concurrent impacts including warmer air temperatures, increased sea level rise, increased storm activity, and an increased intensity in precipitation events. Research has shown there is a direct correlation between fuel combustion and greenhouse gas (GHG) emissions. GHGs are defined as including carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF<sub>6</sub>). CO<sub>2</sub> is the most important anthropogenic GHG because it is a long-lived gas that remains in the atmosphere for up to 100 years.

GHGs have varying global warming potential (GWP). The GWP is the potential of a gas or aerosol to trap heat in the atmosphere; it is the "measure of the total energy that a gas absorbs over a particular period of time (usually 100 years), compared to carbon dioxide" (EPA 2018). The reference gas for GWP is CO<sub>2</sub>; therefore, CO<sub>2</sub> has a GWP of 1. The other main GHGs that have been attributed to human activity include CH<sub>4</sub>, which has a GWP of 28, and N<sub>2</sub>O, which has a GWP of 265 (Myhre et al. 2013). CO<sub>2</sub>, followed by CH<sub>4</sub> and N<sub>2</sub>O, are the most common GHGs that result from human activity. CO<sub>2</sub>, and to a lesser extent, CH<sub>4</sub> and N<sub>2</sub>O, are products of combustion and are generated from stationary combustion sources as well as vehicles. The following formula is used to calculate the Carbon Dioxide Equivalent (CO<sub>2</sub>e).

$$\text{CO}_2\text{e} = (\text{CO}_2 \times 1) + (\text{CH}_4 \times 28) + (\text{N}_2\text{O} \times 265)$$

The FAA has developed guidance for considering GHGs and climate under NEPA, as published in the Desk Reference to Order 1050.1F (FAA 2020). An FAA NEPA review should follow the basic procedure of considering the potential incremental change in CO<sub>2</sub> emissions that would result from the proposed action and alternative(s) compared to the no action alternative for the same timeframe, and discussing

Figure A-1: section 3.4 "Climate" p. 45 of FAA's Draft Programmatic Environmental Assessment for the SpaceX Starship/Super Heavy Launch Vehicle Program at the SpaceX Boca Chica Launch Site in Cameron County [7]

the context for interpreting and understanding the potential changes. For such reviews, this consideration could be qualitative (e.g., explanatory text), but may also include quantitative data (e.g., calculations of estimated project emissions).<sup>18</sup> However, at present, no methodology exists that would enable estimating the specific impacts (if any) that this change in GHGs would produce locally or globally.

### 3.4.2 Study Area

GHG emissions for this project are considered globally since climate change is a global issue. This means GHG emissions are considered at all altitudes for a Starship/Super Heavy launch and for all proposed construction activities.

### 3.4.3 Existing Conditions

The regional climate along the Gulf coast in Cameron County, Texas is characterized by an extended summer season and a mild fall and winter, generally with high humidity. Data from the Brownsville South Padre Island International Airport meteorological station from 1981 through 2010 shows the average daily temperatures range from lows of 63° Fahrenheit in the winter to 84° Fahrenheit in the summer. Average annual precipitation in the region is 27.5 inches recorded over the same period (National Climate Data Center 2012). Wind speeds in the region are usually moderate, although extremely strong winds accompany hurricanes that strike the region. Wind speeds are fairly consistent in the coastal area where the Boca Chica Launch Site is located. Due to Cameron County's coastal location, the area is likely to be more susceptible to the potential impacts of climate change such as sea-level rise and increased frequency of extreme weather events such as hurricanes. Conversely, because this is a coastal area, some protective measures are likely to already be in place, such as hurricane evacuation routes.

Relative sea level rise along the South Texas coast is caused by natural and human-induced land surface subsidence and a global rise in ocean level. Tide gauge records in South Texas, which include the effects of land subsidence, show that relative sea level has risen at a rate of 0.14 inches/year at South Padre Island since 1958. Land subsidence caused by groundwater withdrawal and oil and gas production decreases pore pressures in underlying sediments, allowing further compaction. In addition, sand supply needed to sustain the Gulf shoreline through restoration and replenishment efforts is lacking.

### 3.4.4 Environmental Consequences

The FAA has not established a significance threshold for climate, nor has the FAA identified specific factors to consider in making a significance determination for GHG emissions. There are currently no accepted methods of determining significance applicable to commercial space launch projects given the small percentage of global GHG emissions they contribute. There is a considerable amount of ongoing scientific research to improve understanding of global climate change, and FAA guidance will evolve as the science matures or if new federal requirements are established.

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<sup>18</sup> This analysis is consistent with Executive Order (EO) 13990, *Protecting Public Health and the Environment and Restoring Science to Tackle the Climate Crisis*, 86 Federal Register 7037 (Jan. 25, 2021).

Figure A-2: section 3.4 "Climate" p. 46 of FAA's Draft Programmatic Environmental Assessment for the SpaceX Starship/Super Heavy Launch Vehicle Program at the SpaceX Boca Chica Launch Site in Cameron County [7]

Proposed construction and operations would involve mobile source fuel combustion that would generate GHG emissions from associated launch, landing, and test operations. The GHG emissions associated with the estimated emissions for the Proposed Action is compared to global and U.S. emissions in Table 3-3 below. The maximum number of each launch operation was used in the GHG emission calculations to represent the maximum potential emissions for the Proposed Action.<sup>19</sup> The estimated CO<sub>2</sub> emissions from annual operations of the Starship/Super Heavy Program are significantly less than the total GHG emissions generated by the United States in 2018 and the total CO<sub>2</sub> emissions generated worldwide (Energy Information Administration 2018; WRI 2018). CO<sub>2</sub> emissions from landing of the Starship or Super Heavy booster would be appreciably less than emissions from launches because fewer engines would be relit.

Airspace closures associated with the Proposed Action would result in additional aircraft emissions mainly from aircraft being re-routed on established alternative flight paths and expending more fuel. These emissions include CO<sub>2</sub>, which is a GHG. Based on SpaceX’s proposal, these temporary increases in aircraft emissions could increase up to 26 times per year (Table 2-2). The amount of time that affected aircraft spend being re-routed would be short-term. In addition, the number of aircraft that would be impacted per launch would not be expected to produce additional emissions that would have a notable impact on climate. Therefore, the increases in GHGs caused by short-term airspace closures during commercial space operations is not expected to result in significant climate-related impacts.

In summary, the Proposed Action GHG emissions are not significant and would not cause any appreciable addition of GHGs into the atmosphere.

**Table 3-3. Estimated Carbon Dioxide Equivalent Emissions Comparison**

Annual Emissions Source	Metric Tons Carbon Dioxide Equivalent per Year
Global 2018 Total CO <sub>2</sub> Emissions	3,710 x 10 <sup>11</sup>
U.S. 2018 Total GHG Emissions	5,140 x 10 <sup>6</sup>
Starship/Super Heavy Launches (5)	10,311
Starship Suborbital Launches (20)	868
Starship Landings (23)	346
Super Heavy Landings (5)	316
Starship Static Test Fires (150 seconds )	316
Super Heavy Static Test Fires (135 seconds)	1,504
Methane venting	24,003
Power Plant	9,858
<b>Starship/Super Heavy Operations Annual Total</b>	<b>47,522</b>

Source: EPA 2014, Tables C-1 and C-2 to Subpart C of 40 CFR 98

<sup>19</sup> However, as mentioned in Section 3.3.4.2, the net emissions (i.e., the proposed action emission levels minus the no action emission levels) are estimated to be lower, as the Boca Chica Launch Site is an active launch site.

Figure A-3: section 3.4 "Climate" p. 47 of FAA’s Draft Programmatic Environmental Assessment for the SpaceX Starship/Super Heavy Launch Vehicle Program at the SpaceX Boca Chica Launch Site in Cameron County [7]

Oct. 20<sup>th</sup>, 2021

FAA's Public Hearing

**Public Comment (3-minutes script)**

My name is Elwyn Sirieys, I am a graduate research assistant at the Massachusetts Institute of Technology. I am not speaking on behalf of my organization. The following comments are personal and result from my research efforts over the past few years at MIT.

My work focuses on the one hand on the development of methodologies to assess the environmental impact of launch vehicles, and on the other hand on the optimization of launch vehicle designs for environmental performance.

My comments will focus on the content of Chapter 3, section 4 of the draft PEA. This section addresses the expected impact on Climate.

I will focus on two points given the short time allocated: First - the evaluation of the impact of launch emissions on climate. Second - the interpretation of this evaluation.

**1** - The report states "GHG emissions are considered at all altitudes for a Starship/Super Heavy launch". But by calculating with CO<sub>2</sub>-equivalents the total amount of GHG emissions at all altitudes, the report does not account for the difference between emissions made on the ground versus emissions made in the upper layers of the atmosphere. The impact of any specific combustion product is not identical in every layer of the atmosphere.

Considering that the FAA has an obligation to independently evaluate the contents of the PEA, my question is: *are there ongoing efforts inside the FAA, or in agencies such as NOAA and NASA to develop dedicated methodologies to better assess the environmental impact of launch vehicles?*

**2** - The report states "The estimated CO<sub>2</sub> emissions from annual operations of the Starship/Super Heavy Program are significantly less than the total GHG emissions generated by the United States in 2018". This comparison has limited value for interpretation, so could the FAA propose a new benchmark to evaluate this impact?

**On a final note**, I would like to add that as an aerospace engineer, I know what the development of Starship means to the launch industry, to human exploration and to Science, that it will hopefully make space more accessible. My comments aim at making sure that we know the big picture and anticipate on the environmental impact that launch vehicles will generate.

Thank you, and I look forward to reading your answers.

*Elwyn Sirieys*

Figure A-4: Public comment during the FAA hearing on the Draft PEA, Elwyn Sirieys, October 20th 2021 [7]

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